LSE Middle East Centre

KUWAIT PROGRAMME

A BIOENERGY BLUEPRINT FOR KUWAIT

REGIONAL RESEARCH INSIGHTS, WASTE VALORISATION, FEASIBILITY AND POLICY PATHWAYS

Jean H. El Achkar

LSE Middle East Centre Kuwait Programme Paper Series | 31 | October 2025

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About the Author

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Abstract

Kuwait faces mounting pressure to diversify its energy mix, reduce its dependency on landfills, and meet climate targets under Vision 2035. Despite producing over 2.6 million tonnes of organic waste annually, including food and agricultural residues, sewage, and petroleum sludge, bioenergy currently remains absent from Kuwait's energy portfolio. This paper makes a case for anaerobic digestion (AD) as a strategic enabler of Kuwait's low-carbon transition. Regional bibliometric analysis reveals Kuwait's peripheral role in Middle Eastern bioenergy research, characterised by limited collaboration and a lack of thematic leadership. Building on this, the study models a techno-economic scenario for treating 50% of Kuwait's organic waste via AD, estimating 394 Gigawatt hours (GWh) of renewable electricity annually, 197,538 tonnes of CO_2-equivalent emissions avoided, and over $1.81 billion in profit over 20 years. A comparative framework highlights the fiscal and environmental superiority of AD over landfilling. The findings are translated into a policy roadmap that emphasises pricing reform, integration of the circular economy, public-private investment, and alignment of science and policy. AD offers Kuwait the opportunity to transform waste into renewable assets, enhance energy security, meet climate goals, and lead in regional sustainability.

Introduction

Kuwait's economic trajectory has long been anchored in its vast fossil fuel reserves, with oil and natural gas accounting for more than 90% of the country's total energy consumption.[1] However, as global energy systems shift toward sustainability, the imperative to diversify Kuwait's energy mix has become increasingly urgent. With electricity demand rising at an annual rate of 5% and per capita energy use of 17,760 kilowatt-hours (kWh) in 2024,[2] one of the highest globally, the need for structural reform is critical. Kuwait aims to generate 15% of its energy from renewable sources by 2030, with anticipated reductions in energy consumption of 12% and CO_2 emissions of 33% by 2035.[3] Yet, renewable deployment remains limited, with bioenergy still completely absent from the national mix.[4]

Despite ambitious targets, Kuwait has not capitalised on the vast bioenergy potential of its organic waste streams.[5] Resources such as food waste, agricultural residues, sewage sludge, and petroleum sludge remain underutilised, despite offering compelling opportunities for energy recovery, emissions mitigation, and nutrient recycling. Within the broader Energy-Water-Food Nexus, these undervalued resources can play a pivotal role in driving sustainable development.[6] Anaerobic digestion (AD), a mature and scalable technology, presents a viable pathway to convert these waste streams into renewable electricity and digestate biofertilisers.[7] The dual benefit of energy and material recovery aligns closely with Kuwait's climate and food security objectives under Vision 2035.

Waste management represents both a challenge and an opportunity. Organic waste constitutes approximately 45.3% of Kuwait's municipal solid waste, with food waste alone exceeding 1 million tonnes annually.[8] Most of this waste is sent to landfills, which are rapidly reaching maximum capacity. Kuwait's 18 landfill sites, with only four remaining operational, emit methane (CH_4), one of the most potent greenhouse gases, resulting in

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[1] Hebah Jaber Kamal et al., 'Perspectives of Geography, Environment, and Physiography of Kuwait', in Majda Khalil Suleiman and Shabbir Ahmad Shahid (eds), *Terrestrial Environment and Ecosystems of Kuwait: Assessment and Restoration* (Cham: Springer Nature Switzerland, 2023).

[2] 'Per Capita Electricity Generation', *Our World in Data*. Available at: https://ourworldindata.org/grapher/per-capita-electricity-generation (accessed 15 July 2025).

[3] Akilu Yunusa-Kaltungo, *Key Themes in Energy Management: A Compilation of Current Practices, Research Advances, and Future Opportunities* (Cham: Springer Nature, 2024).

[4] 'Kuwait - Countries & Regions', *IEA Data*. Available at: https://www.iea.org/countries/kuwait/renewables (accessed 15 July 2025).

[5] Jean El Achkar, 'Beyond Black Gold: Breathing Life into Kuwait's Lost Bioenergy', *Middle East Centre Blog*, 1 July 2025. Available at: https://blogs.lse.ac.uk/mec/2025/07/01/beyond-black-gold-breathing-life-into-kuwaits-lost-bioenergy/ (accessed 15 July 2025).

[6] Julian Fleischmann et al., 'OWEFE - Open Modeling Framework for Integrated Water, Energy, Food, and Environment Systems', *Environmental Research: Infrastructure and Sustainability* 3/1 (2003), pp. 1–20.

[7] Ahmed Alengebawy et al., 'Anaerobic Digestion of Agricultural Waste for Biogas Production and Sustainable Bioenergy Recovery: A Review', *Environmental Chemistry Letters* 22 (2024), pp. 2641–68.

[8] Esra Aleisa and Rawa Al-Jarallah, 'Characterisation of Municipal Solid Waste in Kuwait: Sector-Specific Composition Analysis and Implications', *Journal of the Air & Waste Management Association* 74/9 (2024), pp. 623–38.

long-term environmental degradation.[9] Meanwhile, petroleum sludge and sewage sludge are often discarded without treatment, despite their potential energy sources and associated environmental risks.

Globally, food waste accounts for 8–10% of greenhouse gas emissions, with 1.3 billion tonnes wasted annually.[10] In the Gulf Cooperation Council (GCC), Kuwait ranks among the highest in food waste generation, averaging 95kg per person per year.[11] These trends are incompatible with the Sustainable Development Goals (SDGs), particularly SDG 12, which focuses on Responsible Consumption and Production. They also undermine efforts to decarbonise energy systems and reduce public health risks associated with landfill-related pollution.

Despite its technical feasibility and regional relevance, AD remains absent from Kuwait's waste and energy strategy. This gap is puzzling, especially given the successful use of AD in other contexts to valorise (placing value on) complex waste streams, such as sludge and agricultural residues. Bioenergy has the potential to fill a strategic void in Kuwait's renewable energy plans, which remain dominated by solar and wind, yet suffer from intermittency, high capital costs, and very slow implementation.[12] Moreover, fossil fuel subsidies covering 95% of electricity costs further discourage the uptake of alternative energy sources.[13]

A growing body of research supports the case for renewable energy adoption in Kuwait, but the integration of science into policymaking remains weak. Energy efficiency is often hindered by oil dependency, while political and institutional inertia delays reforms.[14] Recent revisions to national targets – including a goal to produce 30% of electricity from renewables by 2030 and reach 50% by 2050 – signal a shift in ambition.[15] However, without clear pathways for implementation, these targets risk remaining aspirational.

Currently, bioenergy contributes 0 percent to Kuwait's energy production. This paper argues that integrating bioenergy into the national energy strategy is not only feasible but necessary to unlock emissions reductions, reduce landfill dependency, and stimulate a

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[9] Anwar F. Al-Yaqout and Mohamed F. Hamoda, 'Report: Management Problems of Solid Waste Landfills in Kuwait', *Waste Management & Research* 20/4 (2002), pp. 328–31; J. Bogner and E. Matthews, 'Global Methane Emissions from Landfills: New Methodology and Annual Estimates 1980–1996', *Global Biogeochemical Cycles* 17/ 2 (2003), pp. 1–18.

[10] Vera Amicarelli et al., 'Global Warming Potential of Food Waste through the Life Cycle Assessment: An Analytical Review', *Environmental Impact Assessment Review* 91 (2021).

[11] 'Food Wastage in Kuwait Is among the Highest in World', *Arab Times*. Available at: https://www.arabtimesonline.com/news/food-wastage-in-kuwait-is-among-the-highest-in-world (accessed 4 October 2025).

[12] Yunusa-Kaltungo, *Key Themes in Energy Management.*

[13] Mariam Alsaad, 'The Unsustainability of Kuwait's Energy System – Examining Kuwait's Energy Problem', *Middle East Centre Blog,* 11 February 2021. Available at: https://blogs.lse.ac.uk/mec/2021/02/11/the-unsustainability-of-kuwaits-energy-system-examining-kuwaits-energy-problem/ (accessed 4 October 2025).

[14] Barakat Elfarra et al., 'The Impact of Energy Security, Energy Mix, Technological Advancement, Trade Openness, and Political Stability on Energy Efficiency: Evidence from Arab Countries', *Energy* 295 (2024); Osamah A. Alsayegh, 'Barriers Facing the Transition toward Sustainable Energy System in Kuwait', *Energy Strategy Reviews* 38 (2021).

[15] 'Kuwait Government Online News', *Kuwait Government Online*. Available at: https://e.gov.kw/sites/kgoenglish/Pages/ApplicationPages/NewsDetail.aspx?nid=26565794 (accessed 4 October 2025).

circular economy. Doing so will also advance Kuwait's Nationally Determined Contributions under the Paris Agreement and SDG targets on climate action, energy, and waste.

To address this strategic gap, the present study undertakes a multi-layered analysis of Kuwait's potential to leverage AD as a climate-aligned waste management solution. First, a bibliometric analysis of 4,113 peer-reviewed publications was conducted to examine Kuwait's position within regional research networks and identify thematic gaps in bioenergy and waste valorisation. Second, the paper develops a techno-economic scenario for AD of 50% of Kuwait's organic waste, projecting electricity output, emissions reductions, and financial returns under policy-supportive assumptions. Third, the study presents a comparative evaluation of AD versus continued landfilling, highlighting the broader climate, economic, and institutional trade-offs. Ultimately, the paper presents a set of targeted policy recommendations designed to integrate bioenergy into Kuwait's sustainability and energy agendas.

Kuwait's Position in Regional Bioenergy Research: A Bibliometric Perspective

Despite its vast organic waste resources and stated ambitions under Vision 2035, Kuwait has remained a peripheral player in the Middle East's evolving bioenergy knowledge ecosystem. To understand this disconnect between potential and policy engagement, a bibliometric analysis was conducted to map regional research trends, assess national collaboration patterns, and identify thematic priorities in the field of bioenergy and organic waste valorisation.

Methodology

The analysis was conducted using VOSviewer software.[16] A dataset of 4,113 peer-reviewed publications was extracted from the Scopus database, covering the period 2015 to 2025. The search strategy targeted relevant literature by including terms such as AD, biogas, bioenergy, biofuels, waste-to-energy, organic waste, food waste, sewage sludge, agricultural waste, and circular economy. To maintain thematic focus, publications related to unrelated energy sources and those from non-relevant disciplines were excluded. Publications were further filtered to retain only those affiliated with institutions in Middle Eastern countries, ensuring geographic relevance to the study.

Two types of bibliometric analyses were performed. First, a country co-authorship analysis was conducted to assess national contributions and collaboration patterns within the Middle East. A minimum threshold of 5 documents per country was applied. Second, a keyword co-occurrence analysis was used to identify the thematic structure of the research field. A minimum occurrence threshold of 30 was applied, resulting in 24 keywords included in the final visualisation.

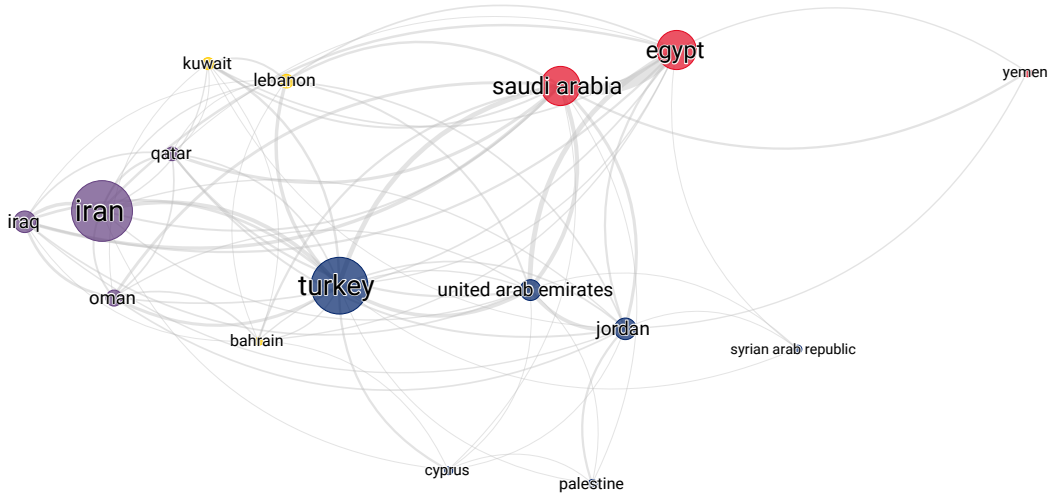
[16] 'VOSviewer - Visualizing Scientific Landscapes', *VOSviewer*. Available at: https://www.vosviewer.com// (accessed 4 October 2025).

Regional Collaboration Patterns and National Participation

The country co-authorship network (Figure 1) reveals a stratified research landscape in the Middle East region, with marked disparities in national participation. Countries such as Turkey, Iran, Saudi Arabia, and Egypt dominate the map in both publication volume and co-authorship density. These nations form central nodes within distinct collaboration clusters. Turkey leads a network extending into the Levant, Iran anchors a group of Gulf-connected states, while Saudi Arabia and Egypt form a relatively independent bilateral hub. This structure reflects the emergence of regional scientific blocs in the field of bioenergy and waste research.

In contrast, Kuwait appears at the periphery, with limited co-authorship links, mainly with Qatar and Lebanon. This marginal presence stands in contrast to Kuwait's economic standing and its declared sustainability goals under Vision 2035. Despite producing some of the highest per capita waste volumes in the region, Kuwait has yet to position itself as a significant scientific contributor to bioenergy collaborations. Its current role underscores a disconnect between policy ambitions and research engagement.

Figure 1: Country co-authorship network of Middle Eastern countries in bioenergy and organic waste research (2015–2025).



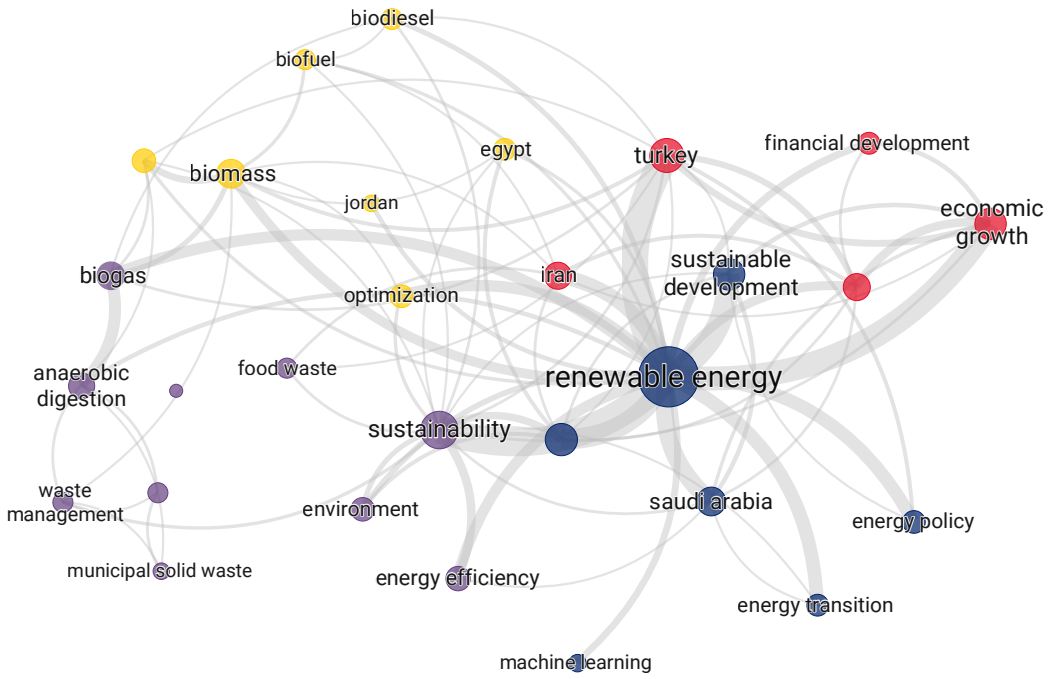
Node size reflects research output; link thickness indicates co-authorship frequency.

Thematic Gaps and Strategic Implications for Kuwait

To complement this structural overview, a keyword co-occurrence map was generated to uncover the thematic priorities of regional research (Figure 2). The analysis revealed four major clusters: biomass and biofuel optimisation (yellow), waste management and anaerobic digestion (purple), economic growth and financial development (red), and renewable energy, policy, and sustainability frameworks (blue). Countries such as Saudi Arabia, Turkey, Iran, Egypt, and Jordan are represented in different clusters, reflecting varied thematic contributions.

Kuwait, however, is absent from the keyword map. This absence is particularly revealing. While the co-authorship analysis shows Kuwait as a minor participant, the lack of thematic presence suggests another issue: Kuwait is not associated with any dominant research trend in the field. It is missing from studies focused on the circular economy, energy transition, or climate-driven waste valorisation, despite these being priorities in national policy documents. This misalignment highlights a gap between research production and strategic national objectives.

Figure 2: Keyword co-occurrence map of Middle Eastern research on bioenergy and waste valorisation (2015–2025).



Node size indicates keyword frequency; link thickness reflects the strength of co-occurrence between keywords.

Together, these two visualisations offer a diagnostic snapshot of Kuwait's position in the regional bioenergy knowledge system. The country is not only underrepresented in collaboration networks but also absent from core thematic discussions. Without a research base connected to regional or global knowledge systems, Kuwait lacks the foundation needed to design, pilot, or scale bioenergy solutions.

Its absent share of bioenergy in the national energy mix is not primarily due to technological or financial constraints, but rather a result of ineffective integration between research and policy. To change this trajectory, bioenergy must be reframed as a strategic knowledge domain. Strengthening institutional collaboration and aligning scientific output with national sustainability goals are essential next steps.

More broadly, the analysis reveals a regional trend: policy-oriented research is present but fragmented. While terms like sustainability, climate change, and energy transition are prevalent, keywords related to policy instruments, governance frameworks, and implementation strategies are scarce. This suggests that, across the Middle East, technical progress in bioenergy research is not yet matched by policy impact. For Kuwait and its neighbours, bridging this gap will require deeper integration of science and policy, as well as more intentional alignment between academic research and national action plans.

While policy alignment remains limited, Kuwait's organic waste landscape presents a powerful yet underutilised opportunity for bioenergy deployment. The upcoming section maps the country's primary waste streams and their respective energy potential, laying the foundation for a scalable treatment strategy.

Organic Waste in Kuwait and Methane Yields

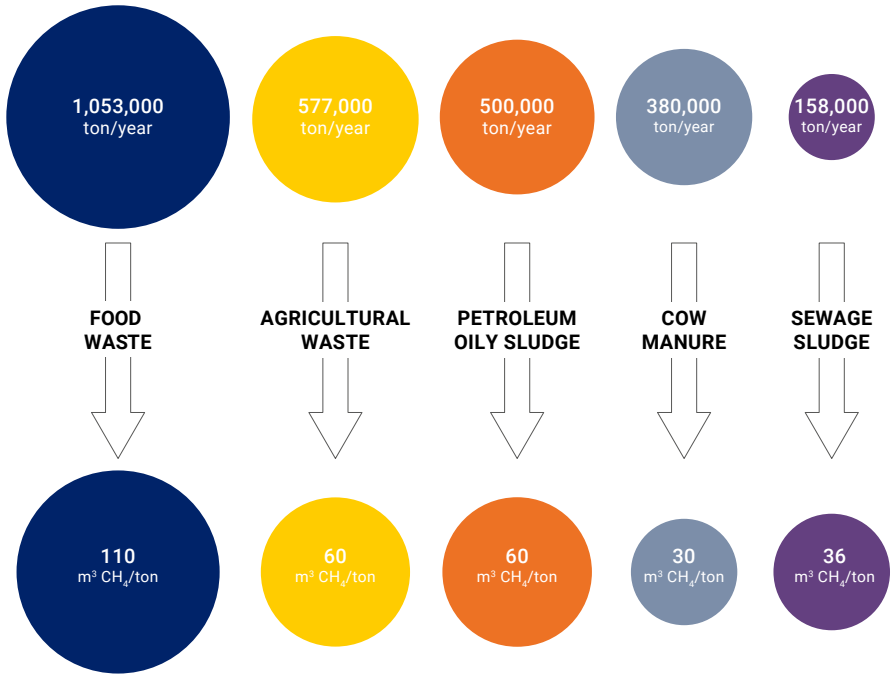
Figure 3 presents a visual overview of Kuwait's five main organic waste streams with significant bioenergy potential: food waste, agricultural residues, cow manure, sewage sludge, and petroleum sludge. Collectively, these streams generate over 2.6 million tonnes annually, with food waste representing the largest share at 1,053,000 tonnes per year,[17] followed by agricultural waste (577,000 tonnes)[18] and cow manure (380,000 tonnes). Petroleum sludge, though industrial in origin and more complex to process, is generated in quantities estimated to reach several million tonnes annually. However, only 500,000 tonnes are considered in this study as a preliminary input, pending further research on their digestibility and safe integration into AD systems. In contrast, sewage sludge, sourced primarily from municipal wastewater treatment plants, contributes approximately 158,000 tonnes per year.[19]

[17] Mohammad Alshawaf et al., 'The Characterisation of Municipal Solid Waste in Kuwait: A Pathway to Reform the Waste Management Sector', *Discover Sustainability* 6/1 (2025), p. 208.
[18] 'Kuwait: Volume of Agricultural Waste 2022', *Statista*. Available at: https://www.statista.com/statistics/645726/kuwait-volume-of-agricultural-waste/ (accessed 4 October 2025).
[19] Mohammad Alshawaf et al., 'The Role of Biomethane from Sewage Sludge in the Energy Transition: Potentials and Barriers in the Arab Gulf States Power Sector', *Applied Sciences* 11/21 (2021), p. 21.

Each waste stream varies significantly in both volume and methane yield per ton. Based on recent regional and international studies, food waste has the highest methane potential, with an average of 110 m^3 CH_4/ton, making it the most energy-rich feedstock. Agricultural residues yield approximately 60 m^3 CH_4/ton, while cow manure produces around 30 m^3 CH_4/ton, mainly due to its lower concentration of volatile solids and the partial degradation of organics during digestion in the animal's gut. Sewage sludge exhibits low to moderate potential at 36 m^3 CH_4/ton,[20] whereas petroleum sludge, despite its handling complexity, can produce up to 60 m^3 CH_4/ton under optimised digestion conditions.[21]

This classification not only highlights the volume and variability of Kuwait's organic waste landscape but also supports strategic prioritisation. The combination of high-yield feedstocks (e.g., food waste) with high-volume but lower-yield streams (e.g., manure and sludge) can enable more balanced, continuous biogas operations. By mapping these streams visually and quantitatively, Figure 3 underscores the systemic opportunity for waste valorisation in Kuwait's transition toward a circular, low-carbon economy.

Figure 3: Quantities and Methane Yields of Kuwait's Main Organic Waste Streams



[20] Jean H. El Achkar et al., 'Anaerobic Digestion of Wastewater Sludge for Improved Energy Recovery: Alkaline Pretreatment Impact, Digestate Quality Assessment, and Reactor Design', *Arabian Journal for Science and Engineering* 48(2023), pp. 16109–21.

[21] Jean H. El Achkar et al., 'Sustainable Conversion of Petroleum Sludge to Methane: A Study on Anaerobic Biodegradability in Batch and Continuous Systems', *Geoenergy Science and Engineering* 250 (2025).

Despite their significant energy potential, these organic waste streams remain largely unvalorised in Kuwait. Over 90% of food waste is landfilled, releasing uncontrolled methane emissions and placing pressure on already limited landfill capacity. Cow manure is partially reused on farms, typically as bedding or ground cover in livestock shelters, but this informal reuse does not harness its energy or nutrient value. Agricultural residues are largely left uncollected or burned in open fields, contributing to air pollution and resource loss. Sewage sludge is often discarded without treatment, representing an environmental liability and a missed opportunity for nutrient and energy recovery. Petroleum sludge, produced in large quantities from oil refining and tank maintenance operations, remains underutilised, with limited efforts to explore its integration into resource recovery systems. The lack of structured valorisation for these waste streams reflects a major gap in Kuwait's current waste and energy strategy. Integrating them into AD systems offers a scalable and proven solution to convert organic matter into biogas, primarily composed of approximately 60% methane, thereby enabling renewable energy production, reducing emissions, and aligning with Kuwait's Vision 2035.

Kuwait's Organic Waste Strategy: Energy and Climate Gains from Anaerobic Digestion

Table 1 outlines the projected outcomes of a strategically phased AD approach to managing Kuwait's organic waste. Rather than assuming full treatment, the study adopts a realistic scenario in which 50% of the country's annual organic waste, approximately 1.33 million tonnes, is directed to AD for energy recovery. The remaining 50% is allocated to complementary management strategies. This includes a significant portion targeted for composting, which is not yet widely practiced in Kuwait but holds strong potential for improving soil health and supporting circular agriculture. The rest would continue to be used in informal but beneficial ways, such as using cow manure as bedding in livestock farms. By combining scalable AD deployment with composting and existing reuse practices, this approach promotes a diversified, practical, and gradually implementable strategy for waste valorisation. The table summarises the major organic waste streams and outlines their respective contributions to bioenergy generation and greenhouse gas (GHG) reduction.

Table 1: Estimated Energy Recovery and Emissions Reduction from the Treatment of 50% of Kuwait's Organic Waste (40% Efficiency)

Waste Type	50% Treated via AD (ton/year)	Methane Yield (m^3 CH_4/ton)	CH_4 Produced (m^3/year)	Energy Content (GWh)	Electricity Output (GWh)	GHG Avoided (ton CO_2-eq)
Food waste	526,500	110	57,915,000	579.15	231.66	115,830
Agricultural waste	288,500	60	17,310,000	173.10	69.24	34,620
Cow manure	190,000	30	5,700,000	57.00	22.80	11,400
Sewage sludge	79,000	36	2,844,000	28.44	11.38	5,688
Petroleum sludge	250,000	60	15,000,000	150.00	60.00	30,000
Total	1,334,000		98,769,000	987.69	394.08	197,538

Each stream differs in methane yield and volume. Food waste, the largest contributor, generates over 57.9 million cubic meters of methane annually, followed by petroleum sludge and agricultural waste, with 15 million and 17.3 million cubic meters, respectively. The total methane produced under this scenario is approximately 98.8 million cubic meters per year, corresponding to an energy content of 987.7 GWh. Assuming an electricity conversion efficiency of 40%, this results in an estimated 394.08 GWh of renewable electricity.

In parallel, the strategy delivers substantial climate benefits, with an estimated 197,538 tonnes of CO_2-equivalent emissions avoided annually. This reflects the controlled capture and utilisation of methane, a greenhouse gas with over 28 times the global warming potential of carbon dioxide over 100 years.[22] In real-world terms, this is equivalent to taking approximately 42,900 gasoline-powered cars off the road each year or planting and growing over 2.1 million mature trees for a decade, based on the US Environmental Protection Agency (EPA) estimates of vehicle emissions and tree carbon sequestration.[23] By displacing fossil-based electricity generation and preventing methane release from unmanaged waste, AD operates as a high-impact mitigation tool, serving both the waste and energy sectors. It aligns with Kuwait's low-carbon development agenda, landfill diversion targets, and national aspirations for a circular economy.

[22] 'Understanding Global Warming Potentials', *Office of Air and Radiation, United States Environmental Protection Agency* (*OAR US EPA*). Available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (accessed 4 October 2025).

[23] 'Greenhouse Gas Emissions from a Typical Passenger Vehicle', *OAR US EPA*. Available at: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle (accessed 4 October 2025).

To illustrate how this strategy translates into concrete energy benefits at the community level, it is useful to consider local electricity consumption patterns. For example, villas in Kuwait's Mubarak Al Kabeer governorate consume an average of 37,956 kWh of electricity per year,[24] based on national energy statistics. With a projected bioenergy output of 394 GWh annually, the electricity generated from AD of just 50% of Kuwait's organic waste could fully power approximately 10,384 villas, covering the annual electricity needs of almost half of all villas in the governorate. This highlights the substantial local impact that targeted waste-to-energy strategies can achieve in advancing sustainability and energy resilience.

Building on these gains, the strategy's performance can be significantly improved through co-digestion, which is the simultaneous anaerobic treatment of multiple organic waste streams.[25] This approach balances the biochemical properties of substrates, such as carbon-to-nitrogen ratios and moisture content, creating more favourable conditions for microbial activity. When properly managed, co-digestion has the potential to increase methane yields by up to 90%,[26] substantially amplifying both energy recovery and greenhouse gas reductions. In Kuwait's context, where diverse waste streams are available in concentrated zones, integrating co-digestion into future AD planning would enhance process efficiency, energy returns, and operational stability.

In parallel, pretreatment techniques such as thermal hydrolysis, mechanical disintegration, and chemical solubilisation can further accelerate substrate degradation and unlock additional methane potential. Several studies have shown that these pretreatment methods can boost methane yields by up to 100% depending on the substrate and conditions used.[27] However, while the technical potential is significant, such enhancements often involve higher capital and operating costs. Therefore, comprehensive techno-economic assessments are needed to evaluate the financial viability of integrating co-digestion and pretreatments into Kuwait's waste-to-energy systems. These assessments should account for infrastructure, energy recovery, environmental benefits, and policy incentives to ensure that optimised AD pathways remain both economically feasible and environmentally effective.

[24] Dalal M. Kassem et al., 'Energy Subsidies and Potential Reforms in the Gulf Region: Investigating Villa Residents' Electricity Consumption and the Factors Influencing It in Kuwait's Six Governorates', *Sustainability* 17/10 (2025), p. 10.

[25] Kaili Liu et al., 'A Comprehensive Review on Food Waste Anaerobic Co-Digestion: Research Progress and Tendencies', *Science of The Total Environment* 878 (2023), p. 163155.

[26] Kefang He et al., 'Review in Anaerobic Digestion of Food Waste', *Heliyon* 10/ 7 (2024).

[27] Jean H. El Achkar et al., 'Influence of Pretreatment Conditions on Lignocellulosic Fractions and Methane Production from Grape Pomace', *Bioresource Technology* 247 (2018), pp. 881–9; Dhamodharan Kondusamy and Ajay S. Kalamdhad, 'Pre-Treatment and Anaerobic Digestion of Food Waste for High Rate Methane Production – A Review', *Journal of Environmental Chemical Engineering* 2/3 (2014), pp. 1821–30.

Financial Viability of Organic Waste-to-Energy Conversion

This section assesses the economic feasibility of AD in Kuwait using a scenario where 50% of organic waste is treated. It outlines expected energy output, investment and operating costs, and revenue streams. Table 2 presents key financial indicators supporting the business case for scaling up waste-to-energy systems. With a total input of 1.33 million tonnes per year and an electricity generation efficiency of 40%, the system is projected to deliver 394.08 GWh of renewable electricity annually. The capital investment required is estimated at $330 per ton of processing capacity,[28] resulting in a total Capital Expenditure (CAPEX) of $440.22 million. Meanwhile, annual Operating Expenditure (OPEX) is $53.36 million, based on an average operational cost of $40 per ton.[29] These estimates are consistent with international benchmarks for AD facilities. Although region-specific data for the GCC or MENA region remain limited, climatic conditions and logistics in this region may drive costs higher. Targeted regional cost studies are therefore recommended to refine these benchmarks.

To assess the financial viability, the model assumes an electricity selling price of $0.10 per kWh, which is moderately higher than Kuwait's current electricity tariffs: $0.046 per kWh for residential users and $0.082 per kWh for businesses.[30] This reflects a cost-recovery approach that would require supportive policy tools, such as green feed-in tariffs, power purchase agreements, or differentiated pricing for renewable energy. Such measures are essential for low-carbon energy systems, where higher upfront costs are justified by avoided environmental damage and greater long-term energy resilience. In real-world terms, achieving such a price could involve introducing feed-in tariffs, differentiated electricity pricing for green energy, or power purchase agreements (PPAs) tailored to attract investment in the circular economy.

The model also includes a government subsidy of $20 million per year, aligned with international practices to mitigate the risk associated with sustainable infrastructure. This support is modest compared to Kuwait's multibillion-dollar fossil fuel subsidies, which cover about 95% of electricity costs. Redirecting even a small fraction of these existing subsidies could readily finance the proposed amount, positioning it as a strategic reallocation rather than a new fiscal burden.

Revenue diversification significantly improves the project's bankability. In addition to electricity sales, carbon credit revenue is estimated at $9.88 million annually, assuming a valuation of $50 per ton of CO_2-equivalent avoided,[31] reflecting current UK market prices.

[28] Fernanda E. Ibarra-Esparza et al., 'Implementation of Anaerobic Digestion for Valorizing the Organic Fraction of Municipal Solid Waste in Developing Countries: Technical Insights from a Systematic Review', *Journal of Environmental Management* 347 (2023), p. 118993.

[29] Ibid.

[30] 'Kuwait Electricity Prices, December 2024', *GlobalPetrolPrices.Com*. Available at: https://www.globalpetrolprices.com/Kuwait/electricity_prices/ (accessed 10 July 2025).

[31] 'UK ETS: Carbon Prices for Use in Civil Penalties', *GOV.UK*. Available at: https://www.gov.uk/government/publications/determinations-of-the-uk-ets-carbon-price/uk-ets-carbon-prices-for-use-in-civil-penalties-2025 (accessed 4 October 2025).

Furthermore, digestate, representing 70% of the treated organic waste and priced at $80 per ton,[32] generates an additional $74.70 million annually, offering value both as a soil amendment and as a means of nutrient recovery. Some references report that digestate is sold for up to $145 per ton, depending on quality and market conditions, suggesting a potential for even greater revenue under optimised conditions.[33] These co-benefits enhance the project's financial performance while supporting agricultural sustainability and circular resource flows. In Kuwait and the GCC, however, actual uptake will depend on domestic demand, export opportunities, and certification standards to secure market confidence.

These combined revenue streams yield a total annual income of $143.99 million and a net annual income of $90.63 million after operating costs. This results in a payback period of 4.86 years, which is well within industry benchmarks for infrastructure investments of this scale. Over a 20-year project lifetime, the total profit is projected to be approximately $1.81 billion, underscoring the strong economic case for scaling up anaerobic digestion as a core pillar of Kuwait's waste-to-energy strategy.

This scenario does not aim to prescribe a specific investment package but rather to highlight the viability of scaling up AD as a strategic component of Kuwait's transition toward a more sustainable and resource-efficient economy. It highlights the crucial role of pricing policy, government incentives, and carbon markets in transforming environmental liabilities into long-term assets.

Table 2: Economic Feasibility of Anaerobic Digestion of Organic Waste in Kuwait: Summary of Key Financial Indicators

Category	Indicator	Value
Project Scope	Treated Organic Waste Electricity Generation Efficiency Electricity Output	1,334,000 tonnes/year 40% 394.08 GWh/year
Capital Costs	CAPEX per Ton of Capacity Total CAPEX (One-time)	$330 $440,220,000
Operating Costs	OPEX per Ton Total OPEX (Annual)	$40 $53,360,000
Revenue Streams	Electricity Revenue Government Subsidy Carbon Credit Revenue ($50/ton CO_2) Digestate Revenue ($80/ton) Total Annual Revenue	$39,408,000/year $20,000,000/year $9,876,900/year $74,704,000/year $143,988,900
Financials	Net Annual Income (Revenue – OPEX) Payback Period Total Profit Over 20 Years	$90,628,900 4.86 years $1,812,578,000

[32] Wojciech Czekała et al., 'Biogas Plant Operation: Digestate as the Valuable Product', *Energies* 15/21 (2022), p. 21.

[33] 'Drying Digestate', *Biomass Magazine*. Available at: https://biomassmagazine.com/articles/drying-digestate-19166 (accessed 10 July 2025).

Strategic Trade-Offs: Reframing Waste Management Through Anaerobic Digestion

To inform future decision-making, this section compares AD with Kuwait's current reliance on landfilling. Table 3 highlights the broader implications of each pathway across environmental, economic, and policy dimensions, underscoring the long-term benefits of transitioning toward circular, low-carbon waste management solutions.

The table outlines the relative performance of both pathways across multiple dimensions. While AD delivers measurable benefits in terms of greenhouse gas mitigation, energy generation, and circular resource use, landfilling continues to incur escalating hidden costs. These include uncontained methane emissions,[34] land and groundwater degradation,[35] and rising public expenditures on health and remediation. AD, in contrast, creates tangible returns both fiscal and ecological by converting organic waste into energy, digestate, and carbon savings.

However, the value of the table lies not only in the comparative figures but in what they reveal about systemic trade-offs. AD offers modularity, co-location with existing infrastructure, and revenue diversification through energy sales, carbon markets, and fertiliser recovery. These features position it as an enabler of Kuwait's Vision 2035 and its climate and energy targets. Landfilling, by contrast, reflects a legacy system that may appear cost-effective in the short term but fails to internalise environmental or opportunity costs.

Notably, the economic return with over $90 million in net annual income and $1.81 billion in long-term value demonstrates that AD is not merely environmentally sound but also financially credible. While assumptions such as the electricity price and subsidy level reflect an idealised policy environment, they offer a blueprint for what could be achieved through targeted reforms. These may include differentiated electricity pricing, fiscal incentives, and the development of carbon trading frameworks, all essential tools for unlocking the full potential of waste-to-energy systems in Kuwait's path toward circularity and decarbonisation.

In essence, the table encapsulates a wider policy question. Should Kuwait continue managing organic waste through an approach that generates no energy, recovers no materials, and increases environmental risk? Or should it adopt a model that delivers climate-aligned infrastructure, diversified revenues, and national co-benefits?

This is not simply a choice between waste treatment technologies. It is a decision about which future Kuwait chooses to build, one rooted in extraction and externalities or one that turns waste into a strategic asset.

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[34] A. Al-Shalan et al., 'Methane Emissions in Kuwait: Plume Identification, Isotopic Characterisation and Inventory Verification', *Atmospheric Environment* 268 (2022), pp. 118763.

[35] Chidambaram Sabarathinam et al., 'Towards Sustainable Groundwater Management in Kuwait: Strategic Directions', in Peiyue Li et al. (eds), *Sustainable Groundwater and Environment: Challenges and Solutions* (Cham: Springer Nature Switzerland, 2025).

Table 3: Comparative Assessment of Anaerobic Digestion and Landfilling of Organic Waste in Kuwait: Climate, Economic, and Policy Perspectives

Dimension	Anaerobic Digestion (AD)	Landfilling
GHG Emissions	Captures methane for energy; avoids 197,538 tonnes CO_2-eq annually	Uncontrolled methane emissions from decomposing organics; among top GHG sources
Land Use	Modular plant footprint; co-locatable with farms or transfer stations	Expands landfill area requirements; land-intensive, irreversible land degradation
Soil and Water Impact	Digestate returns nutrients to soil; no leachate; reduces chemical fertiliser use	Leachate risk to aquifers; no nutrient recovery; long-term soil degradation
Energy Generation	Base-load renewable power (394 GWh/ year); grid-supportive	No energy recovery; opportunity loss
Economic Return	$90.6M net annual income; 4.86-year payback; $1.81B profit over 20 years	Zero income; public costs for landfill operations, remediation and opportunity loss
Policy Alignment	Aligned with Kuwait Vision 2035, NDCs*, SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and related SDGs	Undermines Kuwait's environmental commitments, including Vision 2035, NDCs, and global climate targets
Health and Environmental Impact	Reduces odours, pests, and fires; improves sanitation near communities	Higher exposure to landfill-related pollutants, vectors, and localised environmental stress
System Resilience & Energy Security	Provides renewable electricity and local fertiliser; reduces import dependence	Increases reliance on fossil fuels and imported synthetic fertiliser
Long-Term Fiscal Impact	+$1.81B public value (energy, carbon credits, fertiliser) over 20 years	-$500M at least in net public cost (environmental damage, health externalities, lost energy)

**NDCs: Nationally Determined Contributions under the Paris Agreement*

Policy Recommendations

Unlocking Kuwait's bioenergy potential requires more than technological readiness. It demands coordinated, forward-looking policy reform. Despite the abundance of organic waste and the ambition set by Vision 2035 and the Kuwait National Development Plan (KNDP) 2020–2025, the country lacks the enabling frameworks, institutional mechanisms, and science-policy integration required to operationalise bioenergy at scale.

To translate potential into action, policy must evolve in tandem with market readiness and environmental imperatives. The following five recommendations offer a strategic framework for national implementation.

1. Integrate Bioenergy into National Strategies and Develop a Roadmap

Bioenergy must be formally embedded in Kuwait's climate, waste, and development strategies. National planning documents such as the KNDP and Kuwait's climate reports currently acknowledge emissions goals but overlook organic waste valorisation and anaerobic digestion (AD) as strategic tools.

- Recognise AD and waste-to-energy in national mitigation and adaptation plans.
- Set measurable targets for diverting organic waste streams from landfills to energy systems.
- Co-develop a national bioenergy roadmap with the Kuwait Environment Public Authority (KEPA), Kuwait Institute for Scientific Research (KISR), Public Authority for Agriculture Affairs and Fish Resources (PAAF), Ministry of Electricity and Water and Renewable Energy (MEWRE), and academic institutions.
- Prioritise waste segregation at source, co-digestion hubs, and the conversion of digestate into certified organic fertiliser to support the agricultural sector.
- Establish a national steering committee to coordinate efforts, ensure inter-agency alignment, and monitor progress.

2. Accelerate Deployment Through Public-Private Demonstration Projects

Public-private collaboration is crucial for accelerating the deployment of AD infrastructure while mitigating financial risks and addressing capacity gaps.

- Establish pilot-scale AD plants in high-waste areas such as central food markets, fish harbours, and livestock zones.
- Enable private sector participation through regulatory certainty, risk guarantees, and green procurement frameworks.
- Mandate the supply of clean, sorted organic waste to demonstration sites through government and commercial contracts.
- Monetise outputs through electricity sales, organic fertiliser markets, and participation in emissions credit trading schemes.
- Facilitate knowledge exchange and technology transfer through strategic partnerships with international technology providers.

3. Reform Incentives to Make Resource Recovery Competitive

Current economic structures make landfilling artificially cheap. Shifting toward circularity requires rebalancing financial incentives to favour sustainable waste valorisation.

- Introduce a phased landfill tax to reflect environmental externalities and redirect waste away from disposal.
- Create feed-in tariffs or guaranteed purchase agreements for bioenergy to stabilise revenues and attract investment.
- Simplify grid access for small and medium-scale AD producers to foster distributed generation models.
- Implement organic waste audits and Extended Producer Responsibility (EPR) schemes to boost recovery rates and feedstock quality.
- Launch public awareness campaigns to support behavioural change around waste separation and recycling.
- Without such reforms, the financial case for AD outlined in this study would remain largely theoretical.

4. Strengthen Research, Capacity, and Policy Integration

Scientific knowledge must be translated into actionable policy. Kuwait's current disconnect between research and decision-making is a barrier to innovation and implementation.

- Establish a national Bioenergy Research and Policy Unit to conduct modelling, feasibility studies, and scenario planning.
- Institutionalise science-policy dialogue platforms to align academic output with national development priorities.
- Promote and expand bioenergy, waste valorisation, and circular economy themes across university curricula and research funding frameworks, building long-term human capital.
- Launch a national research funding call dedicated to applied bioenergy solutions, encouraging interdisciplinary collaborations between academia, industry, and government.
- Develop a shared national data platform to track waste flows, methane potential, and project outcomes across sectors.

5. Position Bioenergy in Kuwait's Regional and Industrial Strategy

- Beyond its environmental benefits, bioenergy serves as a lever for economic diversification, regional influence, and post-oil resilience.
- Embed bioenergy into Kuwait's National Industrial Strategy and Small and Medium-sized Enterprise (SME) development plans to catalyse innovation and entrepreneurship.

- Support local manufacturing of AD components (e.g., reactors, Combined Heat and Power units) to build domestic supply chains, create green jobs, and reduce import dependence.
- Develop a green industrial cluster focused on circular energy solutions, organic fertilisers, and low-carbon technologies, positioning Kuwait as a regional hub for sustainable innovation.
- Leverage Gulf-wide platforms to advance regional collaboration on methane reduction, decentralised bioenergy systems, and circular economy initiatives.

Together, these policy directions reframe bioenergy not only as a solution to Kuwait's waste challenge but as a cornerstone of a resilient, diversified, and low-carbon future.

Limitations of the Study

While this study provides a comprehensive assessment of Kuwait's potential for integrating AD into its waste and energy systems, some limitations should be acknowledged.

First, the bibliometric analysis was limited to publications indexed in the Scopus database between 2015 and 2025. Although Scopus offers broad coverage, it may not fully capture the entire spectrum of relevant literature, policy briefs, or local publications in Arabic, potentially underrepresenting Kuwait's actual research contributions. Furthermore, bibliometric tools like VOSviewer focus more on quantitative patterns than on the depth or policy relevance of the research outputs.

Second, the methane yields and energy projections were derived from published international, regional, and local data. While these figures are grounded in literature, variability in waste composition, moisture content, and digestibility could influence actual biogas output. The study assumes uniform efficiency rates across waste streams, which may not reflect real-world operational challenges.

Third, the financial model relies on current estimates for electricity pricing, carbon credit valuation, and government subsidies, which are subject to change. The assumed carbon credit price of $50 per ton reflects current UK market levels but may differ across regions. Testing lower price scenarios (e.g., $20–30) would provide additional robustness and is recommended for future research. As market conditions, policy frameworks, and technological costs evolve, the underlying assumptions and projected figures may require future revision. Additionally, political will and regulatory alignment will be key to realising the projected financial and environmental outcomes. Finally, digestate market absorption and quality remain uncertain, particularly regarding potential contamination risks from petroleum sludge, and will require regulatory oversight and pilot validation.

Despite these limitations, the study provides a robust foundation for evidence-based policymaking and underscores the need for pilot projects and field data to refine future analyses.

Conclusions

Kuwait has a clear window of opportunity to redefine its future in waste and energy management. As this paper demonstrates, Anaerobic Digestion (AD) offers a viable, scalable, and financially credible pathway to convert the country's organic waste streams into renewable energy, reduce greenhouse gas emissions, and advance national targets under Vision 2035, the KNDP, and the 2016 Paris Agreement.

The evidence is compelling. Diverting just half of Kuwait's organic waste to AD could generate 394 GWh of renewable electricity annually, avoid almost 200,000 tonnes of CO_2-equivalent emissions, and yield over $1.81 billion in public value over a two-decade period. These outcomes are not hypothetical; they are within reach with targeted policy action.

Yet the research reveals a critical disconnect: Kuwait remains underrepresented in regional bioenergy research networks and absent from the core thematic areas shaping sustainable waste management in the Middle East. This lack of scientific engagement undermines the country's ability to translate policy ambitions into operational outcomes. Without research-policy alignment, implementation will continue to lag.

Policymakers must act on three fronts. First, bioenergy must be explicitly integrated into Kuwait's energy and climate strategies, with clear targets and financing frameworks. Second, institutional mechanisms must be established to support pilot projects, mobilise public-private investment, and mitigate the risks associated with early-stage adoption. Third, regional and international collaboration should be leveraged to enhance technical expertise and policy design.

AD is not merely a technical fix for waste but a policy instrument that can turn Kuwait's environmental liabilities into national assets. By integrating bioenergy into its core economic and regulatory frameworks, Kuwait can reduce emissions, generate renewable electricity, and restore its soil and food systems. This is both an environmental imperative and a strategic opportunity to lead the region in circular economy innovation. Future research should test the model's robustness through sensitivity analysis of electricity pricing and revenue streams, providing clearer financial outlooks under different market scenarios. Validating these projections through pilot-scale projects in Kuwait will be a critical next step.

The path is proven, the tools are available, and the benefits are measurable. What remains is not the question of how, but the courage to act. The decisive choice before Kuwait is whether to continue burying value or to lead by example and convert waste into resilience, prosperity, and long-term sovereignty. With the right policies, Kuwait can stop managing the waste of the past and start managing the future.

Annex: Equations and Calculations Used

No.	Calculation	Equation
1	Methane Production	CH_4 Produced (m^3/year) = Waste Treated (tonnes/year) × CH_4 Yield (m^3/ton)
2	Energy Content of Methane	Energy (kWh/year) = CH_4 Produced × 10 Energy (GWh/year) = kWh ÷ 1,000,000
3	Electricity Output	Electricity (GWh/year) = Energy (GWh/year) × 0.40
4	GHG Emissions Avoided*	GHG Avoided (tonnes CO2-eq/year) = (CH_4 Produced × 2) ÷ 1,000
5	Digestate Production	Digestate (tonnes/year) = Waste Treated × 0.70
6	Electricity Revenue	Revenue = Electricity Output (kWh/year) × Price (USD/kWh)
7	Carbon Credit Revenue	Revenue = GHG Avoided × Carbon Price (USD/ton)
8	Digestate Revenue	Revenue = Digestate × Digestate Price (USD/ton)
9	Capital Expenditure (CAPEX)	CAPEX = Waste Treated × CAPEX per ton (USD)
10	Operating Expenditure (OPEX)	OPEX = Waste Treated × OPEX per ton (USD)
11	Net Annual Income	Net Income = Total Revenue – Annual OPEX
12	Payback Period	Payback Period (years) = Total CAPEX ÷ Net Annual Income
13	Total Profit Over 20 Years	Profit = Net Annual Income × 20

**Estimates assume methane is captured and combusted, avoiding 2 kg CO_2 per m^3. If released untreated (e.g., in landfills), methane's global warming potential (28–34 times that of CO_2) would result in far greater emissions.*

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