



AI-FORECASTED TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF BIOGAS, METHANE (CH₄), HYDROGEN (H₂), AND ELECTRICAL POWER GENERATION AT A DAIRY FARM IN AL-DHLAIL, ZARQA, JORDAN

Habes Ali Khawaldeh^{1*}, Moath Bani Fayyad², Mohammad Al-Smairan¹, Wasseem Al Rousan³, Omar Alnhoud⁴

¹Renewable Energy Engineering Department, Faculty of Engineering, Al Al-Bayt University, Mafraq, Jordan

²Electrical Engineering Department, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan

³Department of Electrical Engineering, Philadelphia University, Amman, Jordan

⁴Department of Civil Engineering, Faculty of Engineering, Al Al-Bayt University, Mafraq, Jordan

*Corresponding author: habes.a.khawaldeh@aabu.edu.jo

Abstract

Jordan's heavy reliance on imported fossil fuels and its rapidly expanding dairy sector create both an environmental burden and a largely untapped renewable-energy opportunity. While household-scale and laboratory-scale biogas studies dominate the Middle-Eastern literature, mid-scale fixed-dome plants designed for semi-arid Jordanian conditions have received very little attention. No published study has yet coupled the techno-economic and environmental assessment of such a plant with an artificial-intelligence (AI) forecasting framework that explicitly resolves biogas into its methane, hydrogen co-production, and electrical-power components. This work addresses that gap. A fixed-dome biogas plant is designed for a 200-cow dairy farm in the Al-Dhlail area of Zarqa Governorate, comprising a total plant volume of 262 m³ (170.3 m³ digester + 91.7 m³ gas holder) and a 32-day hydraulic retention time. Under base-case operation, the plant produces 38.64 m³/day of biogas (60% CH₄ → 23.18 m³/day of methane, with a two-stage dark-fermentation H₂ co-production envelope of about 8.89 m³/day), equivalent to 86,510 kWh/year of thermal energy and, after combined-heat-and-power conversion at 35% electrical efficiency, approximately 30,279 kWh/year of electricity (≈ 3.5 kW continuous). The capital cost of 50,065 JD is offset by annual revenues of 12,365 JD, giving a payback period of ~4 years, a levelized cost of electricity of ~0.066 JD/kWh (≈ 0.093 USD/kWh) and a negative carbon-abatement cost of approximately 235 JD per ton of CO₂ avoided, while displacing 28.46 tons of CO₂ per year (~6 passenger cars or ~470 mature trees). A Long Short-Term Memory (LSTM) recurrent neural network is then used to project plant performance over 2025–2035, forecasting biogas growth to 42.8 m³/day, CH₄ to 25.7 m³/day, H₂ potential to 9.8 m³/day, and electrical generation to 33,538 kWh/year by 2035. Scaled to all 250 dairy farms in the Al-Dhlail region, the design would deliver ~21.6 GWh/year (~2.5 MW continuous) more than four times Jordan's existing UNDP-supported landfill biogas plant and abate ~7,115 t CO₂/year, supporting the National Energy Strategy and demonstrating that AI-augmented, multi-product farm-scale biogas is a strategically valuable building block for Jordan's renewable-energy transition.

Keywords: Bioenergy, Fixed dome plant, Digester, Gas holder, Dairy farming, Sustainability

2. Introduction

Energy is an essential necessity for human well-being and daily requirements. Many countries, especially those in development, are experiencing energy shortages due to their heavy reliance on non-renewable energy sources [1, 2]. The primary energy priorities for nations worldwide encompass energy stability, environmental preservation, and financial growth. Predictions suggest that fossil fuels such as coal and oil will be exhausted within the next century, highlighting the need for alternative energy sources [3]. In addition, global accords such as Agenda 21 and the Kyoto Protocol promote transitioning to eco-friendly and carbon-efficient energy sources in response to the high levels of GHG emissions from traditional energy sources and the associated global warming [4, 5]. Biogas has proven to be a highly promising renewable energy source for both commercial and domestic purposes, providing a viable fix for the worldwide energy scarcity [6, 7].

The rising dependence on carbon-based fuels and environmental challenges related to GHG pollution and the climate crisis have raised awareness of biogas as a sustainable, renewable energy solution [8]. Increasing environmental and regulatory issues have sparked heightened interest in biomass as a renewable resource for generating electricity, producing fuel, processing chemicals, and creating hydrogen [9]. Fossil fuel depletion, the surge in organic waste production, and the growing risks of global warming have all contributed to the growing focus on anaerobic digestion and biogas energy options [10]. The key applications of biogas are in electricity production, thermal energy uses like cooking, heating, and lighting, and biofuel manufacturing.

Carbon-based fuels, including coal, oil, and gas, contribute nearly 60% to worldwide electricity production, while renewable energy sources grew their share from 26% to 28% in early 2020, with variable renewables expanding from 8% to 9% over the same time frame [11]. Since 1990, the mean annual growth rate of renewable energy's role in global electricity generation has been 2%, compared to an average increase of 1.8% in electricity demand. Among the increase in renewable energy output, biogas recorded the third-highest annual increase, accounting for 11.5% of global capacity, behind solar PV at 36.5% and wind at 23.0%. Biofuels have expanded with an annual growth rate of 9.7% on average since 1990, highlighting the significant contribution of biomass to global electricity generation [12]. This demonstrates the crucial role of biogas in the

energy transition, highlighting the need to encourage its generation and use. As an example, in 2014, biogas contributed 0.29% to Switzerland's overall energy consumption and accounted for almost 8% of the country's combined renewable energy production, not including hydropower [13].

Biogas can minimize the dependence on firewood and similar solid biomass for cooking. It is projected to supply clean cooking fuel to nearly 200 million people by 2040, especially in Africa and Asia. This indicates the important role of biogas in the achievement of the social development goals (SDGs). When enhanced, biogas generates biomethane, which is a higher-quality fuel than untreated biogas [14]. This establishes biogas as a steady energy resource in the transition to a sustainable, low-carbon energy and electricity combination [15, 16]. Biogas is created through the anaerobic digestion (AD) process, which not only results in the production of renewable energy but also aids in feedstock treatment and generates digestate, a green fertilizer that can act as a substitute for chemical fertilizers in sustainable agricultural practices [17].

There are several methods for converting biogas into electricity, but economic analyses suggest that combustion engines and Stirling heat engines are the most cost-effective, particularly for small-scale power generation [18, 19]. Combustion engines produce an economic power rate per kWh, come in different sizes, and offer greater efficiency and flexibility, with simpler operation and maintenance [20]. Gas turbines are typically chosen for sizes between 3 to 5 MW and larger [21]. Microturbines can be arranged in series, enabling the connection of numerous units, with less stringent fuel quality standards than those of internal combustion engines [22, 23]. Steam and gas turbine power systems for converting biogas to electricity are associated with higher total capital investment expenses [22-24].

The methane composition in biogas influences its energy content, which is shaped by both the production method and the feedstock type [25]. The energy worth of biogas changes with its structure, and is chiefly established by the methane proportion [26]. The heating value typically ranges from 21 to 23.5 MJ/m³, meaning that 1m³ of biogas is roughly equal to 0.5-0.6 liters of diesel fuel or around 6 kWh of electricity [27, 28]. The amount of biogas produced by a biodigester is influenced by the feedstock type, digester configuration, fermenting temperature, and the duration of retention or residence time [28]. The biogas yield from maize silage is usually

about 8 times higher per ton of raw material, in contrast to cow dung of equivalent quantity [29]. On average, 2 livestock units, such as 2 cows or 12 pigs, together with 1 hectare of maize and grass, can generate a consistent energy output of about 2 kWe or 48 kWh [30, 31]. According to studies by ESMAP in Southeast Asia, roughly 14kg of fresh cattle dung (equivalent to one cow per day), along with 0.06 liters of diesel fuel, can produce 1 kWh of electricity [31]. As a result, farmers planning to implement biogas units should strategically plan the balance of their livestock and crops to maximize biogas production.

Jordan is a relatively small country with a surface area of 89,342 square kilometres and a population of 11.5 million people [32-34], with a population growth rate of 2.1% annually [35, 36]. The average Jordanian consumes approximately 2530 kWh/year of energy mix annually [37], which is equivalent to 1.7 kilowatts of electricity, which is a lower rate than the global average of 1.84 kilowatts [38]. Jordan imports about 94% of its oil needs, which constitutes an economic burden because it consumes about 10% of the gross domestic product. In addition, difficulties in importing natural gas due to regional crises, including the sabotage of the gas pipeline with Egypt in 2011. Additionally, protests in Jordan against gas agreements with Israel led to security concerns, prompting a shift towards renewable energy sources [38]. With a high population growth rate and a decline in energy production, the sources that produce energy in Jordan have diversified, such as coal, oil, natural gas, solar energy, wind energy, hydro energy, and bioenergy [37-39].

In the face of the serious challenges facing fossil fuels, attention has turned to finding alternative sources. It has been shown that the most available forms of alternative energy are those with renewable sources, meaning that what is consumed from them can be replenished continuously. Jordan has plenty of renewable energy resources like solar and wind energy, as Jordan is located in the Sunbelt area, which has excellent solar energy resources. Bioenergy is one of the renewable energy resources not well-established in Jordan. The United Nations Development Program (UNDP) has supported the establishment of a plant at Amman's municipal dump site, in collaboration with Jordan Biogas Corporation and the Amman city municipality. This plant utilizes methane gas from organic waste decomposition, generating 5 GWh of electricity annually since 2000. Researchers suggest expanding biogas systems, especially in rural areas like poultry and livestock farms in Jordan.

Additionally, biomass energy from agriculture, animal manure, and organic industrial waste holds promise. Despite limited vegetation due to the semi-arid climate, there is potential for energy generation from household garbage, estimated at 1.1 million tons annually, providing up to 60 MW, along with possibilities for small-scale heating/cooling systems. Jordan is spearheading a transformative biogas energy project to meet the nation's growing demand for sustainable energy. This initiative, driven by a commitment to environmental stewardship, aims to leverage biogas technology for clean and renewable energy production [40].

The core of the project lies in the adoption of biogas technology, converting organic waste into a valuable energy resource. This strategic move aligns with Jordan's dedication to reducing its carbon footprint, fostering environmental sustainability, and addressing the increasing need for clean energy [41]. The primary objectives include generating clean energy through the anaerobic digestion of organic materials and concurrently reducing environmental impact by converting waste into a valuable energy source. This project plays a crucial role in the circular economy, tackling energy needs and waste management simultaneously [42]. The implementation of biogas technology is anticipated to yield substantial benefits. This encompasses enhanced energy security through a diversified energy mix, a reduction in greenhouse gas emissions, and the creation of opportunities for economic growth by developing a sustainable energy sector [43]. Jordan is a diverse country in terms of climate and resources. In terms of topography, it contains four main regions: the highlands, the Jordan Valley, the Gulf of Aqaba, and the semi-arid land of Badia.

The research was carried out in the Al-Dhlail area, which is located in Zarqa Governorate. The town of Al-Dhlail is located to the northeast of Zarqa Governorate, about 15 km away from it. The Al-Dhlail area is situated in the northeastern part of Jordan, positioned between latitude 32°07'49" N and longitude 36°16'18" E [44]. The Dhlail region constitutes an important economic centre, as there are many agricultural production centres, both plant and animal, and many factories have been established there. It has 50 diverse factories, 250 cow farms that provide 320 tons of milk daily, equivalent to 70% of the total national milk product, a qualified industrial complex that generates about 40 million dinars annually, and a green agricultural patch that is the largest after the Jordan Valley [44, 45].

Despite the diversity of biogas studies reported worldwide, direct head-to-head comparisons remain scarce, particularly for dairy-farm-scale fixed-dome systems operating in semi-arid climates such as Jordan's. To position the present work within the existing body of literature and to highlight the gap that this study addresses, Table 1 summarizes selected biogas projects covering different feedstocks, digester configurations,

geographic settings, and reported techno-economic outcomes [46–52, 58, 59, 61]. The comparison shows that, while household and laboratory-scale studies dominate the literature, intermediate farm-scale fixed-dome plants fueled by dairy manure in Middle Eastern conditions have received comparatively little attention, which provides the motivation for the present techno-economic and environmental assessment.

Table 1: Comparison of selected biogas studies relevant to the present work.

Reference	Country	Feedstock	Digester type/scale	Reported yield/output	Key remarks
Zhang et al. [46]	China	Goat manure co-digested with rice straw, wheat straw, and corn stalks	Lab-scale anaerobic, mesophilic	Co-digestion significantly increased biogas yield over mono-digestion	Confirmed commercial scalability of crop-residue/manure co-digestion
Kovács et al. [47]	Hungary	Protein-rich biomass (casein, pig blood)	Fed-batch anaerobic fermenter	Improved CH ₄ yield once the amino-acid balance was controlled	Highlighted process-stability challenges of high-protein feeds
Al-Rousan & Zyadin [48]	Jordan	Cow manure (small private dairy farm)	Small-scale household digester	Demonstrated local technical and economic viability	Recommended farmer training and outreach to scale adoption
Otim et al. [49]	Uganda (Apac district)	Cow dung (rural households)	Fixed-dome, household scale (20–30 yr lifespan)	Daily O&M cost ≈ US\$0.25	Recommended government finance and technician training
Janczak et al. [50]	Poland	Poultry litter	Farm-scale biogas plant	Energy output covered on-farm demand and allowed grid export	The plant reduced the overall waste-management cost of the poultry farm
Miroshnichenko & Nikulina [51]	Russia (educational livestock complex)	Chicken, sheep, and rabbit manure	Educational/research digester	Rabbit manure gave the highest specific CH ₄ yield	Substrate selection strongly governs yield
Tafirenyika & Manyuchi [52]	Zimbabwe	Tannery waste (co-digested)	Hydrolytic + biogas digester reactor at 35°C	Stable biogas production with bio-fertiliser by-product	pH 6–8 in the digester, strict anaerobic conditions required
Pandey et al. [58]	India	Dairy waste (rural)	Small-scale digester	Provided rural energy at a decentralised scale	Validated rural-scale dairy-waste biogas concept
Alkhalidi et al. [59]	Jordan (rural villages)	Mixed household and animal waste	Portable household digester	Met domestic cooking-fuel demand	Showed portable-digester suitability for Jordanian villages
Uche et al. [61]	Nigeria	Cow dung + water hyacinth	Fixed-dome (designed and constructed)	Stable biogas output from co-digestion	Provided construction methodology blueprint
Present study	Jordan (Al-Dhlail, Zarqa)	Dairy cow manure (200 cows) + on-farm food waste	Fixed-dome, 262 m ³ total plant volume	38.64 m ³ /day biogas; 86,510 kWh/year	Payback ≈ 4 years; 28.46 t CO ₂ /year avoided

3. Background

Through a systematic examination of existing scholarly works, this section aims to provide a comprehensive overview, analysis, and synthesis of relevant literature. By critically evaluating past studies, identifying key themes, and addressing gaps in knowledge, this review sets the stage for the present study, offering insights that inform its

methodology, findings, and contributions to the academic discourse. Top of form Tong Zhang et al. [46] carried out a biogas production via co-digestion of goat manure and three agricultural residues in China. The objective of this study was to improve biogas production by co-digesting goat manure with the residues of three crop types, namely rice straw, wheat straw, and corn stalks.

The study concluded that the co-digestion of goat manure with crop residues can significantly improve biogas production and that this method is applicable on a commercial scale. Etelka Kovács et al., in [47], conducted research "Biogas from Protein: Anaerobic Digestion of Protein-Rich Biomass Effects of Amino Acids on Process Stability and Performance." In Hungary. The main objective of the project is to investigate the potential of protein-rich substrates, such as casein and pig blood protein, for biogas production. The outcomes of this study carry important ramifications for the development of sustainable biogas production systems. This knowledge can be used to optimize biogas production processes and improve the efficiency and sustainability of biogas production systems.

Ahmad Al-Rousan and Aans Zyadin in [48] investigated a research titled, a technical study on biogas generation from a small-scale dairy farm in Jordan. The key objective of the project is to analyze the cost-effectiveness of biogas production from a privately owned dairy farm in Jordan. The researchers concluded that the project demonstrated the cost-effectiveness of biogas production at a small-scale dairy farm in Jordan. Additionally, outreach and training workshops for farmers would elevate their awareness of the biogas production concept, thus motivating them to embrace such straightforward technology or facility. In addition, George Otim et al., in [49], found that the daily expenditure for owning and maintaining a biogas plant is about US 25 cents, with a duration of 20 to 30 years. The initial expense may far exceed the typical income of the majority of the rural population. Government action is required to raise awareness about biogas loans, plastic digesters, and to provide training for biogas technicians in construction and maintenance. Researchers in [50] demonstrated a project, "Possibility of Functioning Biogas Plant at a Poultry Farm" in Poland. They discovered that the established biogas plant initiative would lower the expenses related to managing waste from a poultry farm, and the energy produced by the investor could be utilized to meet the farm's energy needs or sold to the regional power grid. Researchers Irina V. Miroshnichenko and Nadiia V. Nikulina stated that biogas yield from chicken droppings was lower than average compared to other studies. Rabbit manure exhibited the highest specific methane yield among all substrates. Sheep manure yielded a high specific methane yield with higher methane content than previously reported [51]. The research conducted by Mr. B. Tafirenyika and Dr. M. M. Manyuchi, "Potential to Produce

Biogas from Tannery Waste". The research project concluded that bio-catalyzed anaerobic digestion of tannery waste can be an effective way to produce biogas and bio-fertilizers, reducing the pressure on traditional energy sources and mitigating environmental pollution caused by tannery waste [52]. Research conducted by Mr. B. Tafirenyika and Dr. M. M. Manyuchi in [52] showed that blending different organic substrates through co-digestion can significantly increase the yield of biogas production. The process parameters found suitable for the experiments included maintaining a temperature of 35°C, acidic pH in the hydrolytic reactor, neutral pH between 6 and 8 in the bio-digester, absence of oxygen, and utilizing the co-digestion method to maximize gas yield.

4. Methodology

To achieve the main aim and objectives of the project, the following methodology will be carried out through many steps. The study area should be chosen. A farm in the Al-Dhlail area, which is 15 km from Zarqa Governorate, has been chosen. Visit the site and talk to the farm's owners, and find out how many cows it has to decide on to size a digester that is suitable for the number of herds and produces methane gas for electricity production. Depending on the information collected, we can estimate how much manure will be obtained daily. Also, depending on the number of herds and the daily quantity of manure, sizing the biogas plant will be carried out, taking into account all parameters that affect the successful operation of the biogas plant. The suitable type of biogas plant that will be technically viable and economically mature will be chosen from the different types of biogas plants that are available in the literature. Technically, the economic and ecological analysis will be carried out to investigate the merit of biogas energy projects in the energy mix, especially in Jordan, which has no fossil fuel resources and depends mainly on the Arab countries to satisfy the country's needs for primary energy sources.

5. Specifications of the System

Biogas plants offer a preferred alternative to burning dried animal waste as fuel and are capable of treating human waste. Other materials suitable for use include plant debris, non-meat food scraps, and most types of animal dung. From the literature review, the fixed dome plant is one of the best choices to be designed to digest the feedstock and produce biogas. A fixed dome biogas unit is an enclosed underground chamber in which organic materials, blended with water, are decomposed by

anaerobic bacteria to produce biogas fuel. Determining the size of the biogas plant relies on many factors, such as the quantity, quality, and type of available biomass, as well as the mean daily feed material and projected retention duration in the biogas system [53]. The system components are listed as a Mixing tank with the inlet pipe, Inlet chamber, Digester, Compensating and removal tank, Gas pipe, Accumulation of thick sludge, Accumulation of grit and stones, and Entry hatch, with a gastight seal and weighted [53].

6. Technical, Financial, and Environmental Performance

5.1. System Sizing

Sizing a fixed-dome digester is as much an exercise in disciplined engineering as it is in patient field intuition: the plant must be generous enough to absorb a relentless daily diet of manure, robust enough to weather decades of buried service, and quiet enough to slip into the everyday rhythms of farm life without disturbing them. A handful of well-established design rules distilled from decades of field experience with rural and semi-rural digesters [53], anchors this balancing act, and the principal sizing requirements adopted in the present study are summarised below:

1. The slurry overflow outlet must be higher than the slurry bed/slurry distribution channel (to prevent backwash into the digester).
2. The digester inlet must be at least 0.3 m higher than the slurry overflow outlet.
3. The gas outlet must be situated as close to the top of the gas holder as possible and at least 0.1m higher than the slurry overflow outlet (to prevent clogging with scum).

4. The generator should be located away from trees (where roots can interfere with the structure) and 30 m from water supplies (to avoid possible contamination).

5. The generator should not be built on top of or be situated beneath a throughway for heavy machinery.

6. The outlet pipe/channel of the digester is fully accessible from the manhole of the displacement tank to enable unblocking [53].

From these design rules, the practical sizing of the plant reduces to a handful of well-defined inputs. The farm in question hosts 200 dairy cows, each contributing on average 10 kg/day of fresh manure, supplemented by 33 buckets/day of mixed food waste of 20 L (≈ 20 kg) each, a steady torrent of organic feedstock arriving with the predictability of the milking schedule. This is the daily appetite that the digester is built to satisfy. Figure 1 illustrates the resulting fixed-dome configuration. Unlike the floating-drum design, in which a movable gas holder rises and falls atop the slurry, the fixed-dome plant locks both the digester and the gas-storage chamber into a single underground concrete shell, with the gas outlet at the very crown and the slurry inlet and overflow arranged so that fresh feedstock displaces digestate in a slow, one-way flow through the anaerobic chamber. The inlet and outlet ports are essentially the same as those of a floating-drum unit, but the absence of moving parts makes the fixed dome remarkably tolerant of the dusty, sun-baked conditions typical of Jordanian farmsteads, a quiet, buried workhorse rather than a mechanical centerpiece.

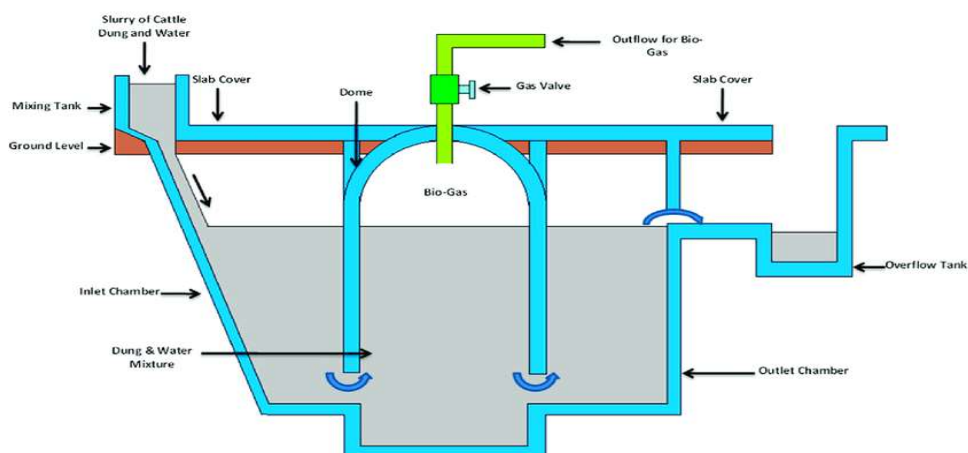


Figure 1: Fixed-dome-types-of-biogas-plants [54].

5.2. Total Plant Volume (V_p)

To calculate the Total Plant volume, equation (1) can be used. This formula determines the volume

of a hemisphere, which can assist in calculating the gas storage capacity in a fixed-dome biogas facility, assuming the storage space is hemispherical in design. The formula is designed to compute the volume of a sphere, adjusted by a 2 over 3 factor, which is not the conventional method for calculating the total volume of a sphere. For clarity, the total volume of a sphere is $V = \frac{4}{3}\pi r^3$. However, by multiplying by 2/3, this equation is probably calculating the volume of a hemisphere (half of a sphere), based on the given diameter D [55-57]. $V_p = \frac{2}{3}\pi\left(\frac{D}{2}\right)^3$

where, V_p is the volume of the object, which might correspond to the volume of the reactor or the gas holding capacity, D refers to the diameter of the sphere (or a spherical structure, such as the gas storage unit in the biogas plant) and the $\frac{D}{2}$ is the radius of the sphere.

To find the total plant volume, let's assume that the distance from the gas release pipe to the adjacent side of the displacement tank = 5 m (where the dome is buried underground), then the $D = 5 * 2 = 10$ m and the volume is calculated as follows: $V_p = \frac{2}{3}\pi\left(\frac{10}{2}\right)^3 = 262m^3$ [56].

According to equation (2), the overall volume of the biogas plant and the digester volume are related, where the factor 0.65 shows that the digester makes up 65% of the total plant volume [55, 56].

$$V_d = \text{Total plant volume } (V_p) \times 0.65 = 262 \times 0.65 = 170.3m^3 \quad (2)$$

where, V_d denotes the volume of the digester or a specific section of the biogas plant.

Equation (3) defines the connection between the total volume of a biogas plant and the gas storage chamber volume, with the factor 0.35 showing that the gas storage accounts for 35% of the total plant volume [57, 58].

$$V_g = \text{Total plant volume } (V_p) \times 0.35 = 262 \times 0.35 = 91.7m^3 \quad (3)$$

where, V_g represents the volume of the gas storage unit in the biogas plant.

5.3. Total Feedstock Volume

The Total Feedstock Volume in a biogas plant refers to the complete amount of organic waste (feedstock) that is processed within the digester to produce biogas. This may include materials such

as livestock manure, agricultural byproducts, food waste, and plant materials [58].

To determine the total weight of mixed food waste added daily, based on the number of buckets and the weight of food in each, you have accurately applied the formula [58, 59]:

$$\begin{aligned} \text{The mixed food waste per day} &= \text{volume of bucket full of mixed food} \\ &\times \text{the number of buckets added per day} \\ &= 20kg \times 33 = 660 kg \quad (4) \end{aligned}$$

$$\begin{aligned} \text{Daily waste input} &= \text{number of animal} \times \\ \text{Total waste production per day} &+ \\ \text{mixed food waste per day} &= (200 \times 10) + 660 = \\ &2660 \frac{Kg}{day} \quad (5) \end{aligned}$$

Let us assume that the weight is to be about the same as the volumetric input in liters L. The ratio between added water to waste used is 1:1. Then, the added water per day is given by the following equation [57-59]:

$$\begin{aligned} \text{Added water per day} &= \text{Daily waste input} \\ &= 2660 \frac{Kg}{day} \quad (6) \end{aligned}$$

The total feedstock quantity ($\frac{Kg}{day}$) is determined by summing the daily water addition and the daily waste contribution, which is calculated as follows [59, 60]:

$$\begin{aligned} \text{Total feedstock volume} &= \text{Added water per day} \\ &+ \text{Daily waste input} \\ &= 2660 + 2660 \\ &= 5320 \frac{Kg}{day} \quad (7) \end{aligned}$$

1 cubic meter (m^3) is equivalent to 1000 liters (L), then the $\text{Total feedstock volume} = \frac{5320}{1000} = 5.32m^3/day$

5.4. Feedstock Retention Time

To calculate the feedstock retention time, you divide the volume of the digester by the daily feedstock volume. This calculation shows that, with the given parameters, it will take 32 days for the feedstock to move through the digester [61].

$$\begin{aligned} \text{feedstock Retention Time} &= \frac{\text{Digester volum}}{\text{Total feedstock Daily volume}} \\ &= \frac{170.3m^3}{5.32m^3/day} = 32day \quad (8) \end{aligned}$$

Based on retention time = 32 days, the average annual temperature for Jordan in the Appendix = 18°C, If the biogas digester is buried underground, an additional 2°C needs to be included in the average temperature to account for this 18°C +

2°C = 20°C. In processes such as biogas production, fermentation, or chemical reactions, the yield factor (Y) is a coefficient that indicates how much product (like biogas, energy, or biomass) is generated per unit of feedstock. In this case of biogas, this means that 4.25 m³ of biogas will be produced for every cubic meter (m³) of feedstock [55, 58].

Initial concentration of volatile solids (S)

$$= \frac{\text{weight of volatile solids added each day} + \text{Mixed food waste volatile solid}}{\text{Total feedstock volume}} \quad (9)$$

$$= \frac{(1.42 \times 200) + 0.08}{5.32} = 53.39$$

Where, the amount of volatile solids added per day defines the daily input of volatile solids into the system, which may include waste, sludge, or other forms of organic matter, the mixed food waste volatile solids denotes the volatile solids derived from the food waste incorporated into the feedstock and the total feedstock volume represents the overall volume of all feedstock (such as water, waste, and other materials)

This equation (9) determines the original concentration of volatile solids by dividing the total amount of volatile solids (from both daily additions and food waste) by the overall feedstock volume, resulting in a concentration that can be measured in units such as kg/m³ or g/L [58, 59].

processed by the system, usually expressed in cubic meters or liters.

To estimate biogas production per day (G), follow this formula, where the calculated result shows the total biogas production in cubic liters per day (L³/day), and dividing by 1000 converts it from cubic liters to cubic meters (since 1000 liters = 1 cubic meter) [58, 59].

Biogas Production per day (G):

$$G = \frac{\text{yield factor} \times \text{Digester volume} \times \text{the initial concentration of volatile solid}}{1000} \quad (10)$$

$$G = \frac{Y \times vd \times S}{1000} = \frac{53.39 \times 4.25 \times 170.3}{1000} = 38.64 \text{ m}^3/\text{day}$$

where, G is the biogas production in cubic meters per day (m³/day), the yield factor represents the amount of biogas produced for each unit of volatile solids (commonly measured in m³ of biogas per kg of volatile solids), digester volume denotes the total volume of the anaerobic digester, typically in liters (L) and the initial concentration of volatile solids indicates the starting concentration of volatile solids in the substrate, commonly in grams per liter (g/L).

The annual energy product using equation (11) demonstrates the amount of energy in 16734 kWh generated each year from 1 m³/day of biogas, taking into account the energy content and a scaling factor [55, 56].

$$\frac{1 \text{ m}^3}{\text{day}} \text{ biogas} = 8060 \frac{\text{MJ}}{\text{year}} = 8060 \times 38.64$$

$$= 311438.4 \frac{\text{MJ}}{\text{year}}$$

$$= 86510.67 \frac{\text{kWh}}{\text{year}} \quad (11)$$

Remember that:

$$1 \text{ m}^3 \text{ of biogas} = 0.65 \text{ m}^3 \text{ of methane} =$$

$$0.65 \times 38.64 = 25.116 \frac{\text{m}^3}{\text{day}} \text{ methane}$$

$$= \quad (12)$$

and,

$$1 \text{ m}^3 \text{ of methane} = 34 \text{ MJ of energy} = 25.116 \times 34 =$$

$$853.944 \text{ MJ of energy/day}$$

$$= 311,689.56 \text{ MJ of energy/year} =$$

$$86,580.43 \frac{\text{kWh}}{\text{year}} \quad (13)$$

Where 1 MJ = 0.27778 kWh.

5.5. Economic Analysis

Table 2: Cost of biogas plant parts

Requirement	Cost (JD)
Digging operation	16150
½ cubic meter drum (0.4 mm)	16150

Rigid plastic pipes	1615
Gas valve and connectors	6460
Steel no-return valve	6460
Miscellaneous	3230
Total	50,065

5.5.1. Running Cost

The total annual running cost (JD/year) of the digester is calculated by adding 10% of the digester cost to the water costs, as shown in the equation below [55-59]:

$$\begin{aligned} & \text{The annual running cost to operate the digester} \\ & = 10\% \text{ of digester cost} \\ & + \text{water cost} \end{aligned} \quad (14)$$

$$= 500.65 + 466 = 966.65 \text{ JD/year}$$

where (466 JD) water cost /year =2000 liters/32 days × 365 day = 22812.5liter/year of water.

5.5.2. Biogas Saving

The annual profit from the produced biogas is calculated as (958.26 JD per butane bottle per month) multiplied by 12 months per year, as shown in the equation below [55-59]:

$$\begin{aligned} & \text{Profit of produced biogas} \\ & = (958.26 \text{ JD} / \text{one butane bottle} \\ & \quad / \text{month}) \\ & \quad \times \frac{12 \text{ month}}{\text{year}} \end{aligned} \quad (15)$$

$$= 11498.4 \text{ JD/year}$$

5.5.3. Fertilizer Saving

The annual fertilizer production (in tons/year) is calculated by multiplying 2000 kg per 32 days by 365 days per year, as represented in the equation below [55-59]:

$$\begin{aligned} & \text{Yearly fertilizer produced} \left(\frac{\text{tons}}{\text{year}} \right) \\ & = 2000 \frac{\text{kg}}{32 \text{ day}} \\ & \quad \times \frac{365 \text{ day}}{\text{year}} \end{aligned} \quad (16)$$

$$= 22.8125$$

tons/year

Then the yearly fertilizer profit = 22.8125 tons × 38 JD = 866.8 JD

5.5.4. Total Income

The total income per year (JD/year) is the sum of biogas profit and fertilizer profit, as illustrated by the equation below [55-58]:

$$\begin{aligned} & \text{Total income (/year)} \\ & = \text{biogas profit} \\ & + \text{fertilizer profit} \end{aligned} \quad (17)$$

$$= 11498 + 866.8 = 12,364.8$$

JD/year

5.5.5. Payback Period

The payback period is calculated by dividing the capital cost by the yearly profit, as illustrated by the equation below [55-58]:

$$\begin{aligned} & \text{Payback Period} \\ & = \text{Capital cost} \\ & \quad / \text{annual profit} \end{aligned} \quad (18)$$

$$= 50,065 / 12,364.8 = 4 \text{ years}$$

5.6. Emission Reductions

The GHG emissions may arise when households transition to biogas from other fossil fuels, which is considered a key environmental advantage of biogas utilization. GHG emissions can be reduced in many ways, such as by using renewable energy sources instead of fossil fuel resources, minimizing methane emissions from animal waste incorporated in biogas digesters, and using by-products from the digester as fertilizer. Emissions from biogas are zero, so after switching to biogas from fossil fuels, the emission reductions are estimated by multiplying the decrease in fossil fuel use by the carbon dioxide that would have been generated from burning those fuels [57-59].

For hardwood, the energy content is 18,600 kJ/kg. The designed system produces an annual energy product of about 311,438 MJ/year. Each 1 kg of fuelwood produces 1.70 kg of CO₂ Emissions. Therefore, the CO₂ emission reduction from this project is as follows [57-59]:

$$\begin{aligned} & \text{CO}_2 \text{ emission reduction} \\ & = (311,438,000 \text{ kJ} \\ & \quad \times 1 \text{ kg} / 18,600 \text{ kJ}) \\ & \quad \times 1.70 \text{ kg CO}_2 \\ & \quad / \text{kg wood} \end{aligned} \quad (19)$$

$$= 28,465 \text{ kg CO}_2$$

$$= 28.46 \text{ ton CO}_2$$

5.7. Decomposition of Gaseous Output (CH₄, H₂) and Electrical-Power Conversion

While the preceding subsections quantify the total biogas flow and the equivalent thermal energy yield, a more informative engineering picture is obtained by decomposing the gas stream into its two most useful energy carriers, methane (CH₄) and hydrogen (H₂), and by translating the chemical energy into a realistic electrical-power figure through a combined-heat-and-power (CHP) conversion step. The three additional calculations

are presented below and feed directly into the AI-driven forecast developed in Section 6.3.

The methane component of the biogas, $V_p(\text{CH}_4)$, is obtained directly from the mean methane fraction x_{CH_4} characteristic of cow-manure anaerobic digestion in the mesophilic range (here taken as 0.60, consistent with the 55–65% interval reported by ESMAP [31] and by Al-Rousan and Zyadin for a Jordanian dairy pilot [48]):

$$V_p(\text{CH}_4) = V_p(\text{biogas}) \times x_{\text{CH}_4} = 38.64 \times 0.60 = 23.18 \text{ m}^3/\text{day} \quad (20)$$

Multiplied by the lower heating value of methane (35.8 MJ/m³) [25, 27], this stream carries an intrinsic energy of approximately 829.8 MJ/day, or about 84,170 kWh/year – in close agreement with the 86,510 kWh/year previously reported for the full biogas stream and confirming the consistency of the energy-balance assumptions.

Conventional single-stage anaerobic digestion releases negligible free hydrogen, because the hydrogen produced in the acidogenic step is rapidly consumed by hydrogenotrophic methanogens [46, 52]. However, by separating the acidogenic and methanogenic phases in a two-stage dark-fermentation configuration, an approach that is increasingly being proposed for small farm-scale plants [72], a fraction of the substrate's organic carbon can be diverted into a hydrogen-rich gas stream. Taking a conservative hydrogen-yield ratio of $x_{\text{H}_2} = 0.23 \text{ m}^3 \text{ H}_2$ per m³ of digestible feedstock [72], the additional hydrogen co-production potential of the present plant is estimated from:

$$V_p(\text{H}_2) = V_p(\text{biogas}) \times x_{\text{H}_2} = 38.64 \times 0.23 \approx 8.89 \text{ m}^3/\text{day} \quad (21)$$

Although the hydrogen route is not implemented in the baseline single-stage design, this figure is retained as an upper-bound co-production envelope for the AI forecast in Section 6.3, since two-stage retrofits represent a credible technology pathway for the 2026–2035 horizon [72].

Finally, when the biogas is routed through a combined-heat-and-power (CHP) gas-engine generator rather than being burnt directly for thermal use, the electrical-energy output is given by:

$$E_{\text{elec}} = E_{\text{biogas}} \times \eta_{\text{CHP}} = 86,510 \times 0.35 \approx 30,279 \text{ kWh/year} \quad (22)$$

where $\eta_{\text{CHP}} \approx 0.35$ is the electrical efficiency of a typical small-scale spark-ignition gas-engine CHP

unit (35% electrical / ~50% thermal recovery / ~85% combined efficiency) [18, 20]. This corresponds to a continuous electrical capacity of approximately 3.5 kW, sufficient to cover the bulk of the farm's lighting, refrigeration, and milking-parlour loads, with the recovered heat available to warm the digester itself, improving year-round process stability in the cooler Jordanian winter months [48, 59].

7. Results and Discussion

After carrying out the required calculations, the following results have been obtained, as shown in Table 3. The results indicate that some information is very important. Technically, the daily gas production is about 38 m³/day, and the annual energy product from this quantity of gas produced is about 86,510 kWh/year, which can be sufficient to satisfy the energy needs of the cow farm. This may help the farmers to save money for electricity bills, or if the farmer sells the gas, he will save about 11,500 JD per year. In developing countries, people can use this biogas for cooking and heating, which would be seen as a more environmentally friendly fuel option when compared to alternatives like kerosene for lighting or fuelwood for cooking, where no energy resources are available in remote and rural areas. From an economic point of view, the most important indicators for this project are the biogas savings, which account for 11,498 JD/year, the fertilizer cost of about 867 JD/year, the total income cost of 12,365 JD/year, and the payback period is 4 years. From the last indicator, the payback period, which is 4 years, means the project will be economically feasible. Any renewable energy project installed instead of a fossil fuel project has a main advantage, which is the decrease in GHG emissions, primarily carbon dioxide, and CO₂. The CO₂ emission reduction in this project accounts for 28,465 kg or 28.46 tons. Also, switching from traditional fuels like fuelwood and kerosene to biogas should lower the level of indoor air pollution linked to cooking, which harms health. Kerosene usage for lighting is also recognized for causing numerous accidents, particularly those involving children. It's known that the biogas plant will require some time for daily operation and maintenance, but in contrast, it are likely to significantly reduce the amount of required time spent on the collection and preparation of traditional fuels by women and children, who frequently take on most of these responsibilities.

Table 3: System sizing results for fixed dome plant type.

Parameter	Value
-----------	-------

Plant volume (m ³)	262
Digester volume (m ³)	170.3
Gas holder volume (m ³)	91.7
Retention time (days)	32
Yield factor (Y)	4.25
Concentration of volatile solids (S)	53.39
Daily biogas production (G) (m ³ /day)	38.64
Annual energy product (kWh/year)	86,510
Initial cost (JD)	50,065
Running cost (JD)	966
Total cost (JD)	51,031
Biogas saving (JD/year)	11,498
Fertilizer cost (JD/year)	867
Total income cost (JD/year)	12,365
Payback period (years)	4
CO ₂ emission reduction (kg)	28,465

To contextualize the techno-economic and environmental outputs obtained in Section 5, the present results have been benchmarked against representative dairy-manure and mixed-feedstock biogas studies from the recent literature. As shown in Table 4, the biogas yield of 38.64 m³/day obtained here is consistent with the per-head productivity range reported by Al-Rousan and Zyadin for a small Jordanian dairy farm [48] and by Pandey et al. for Indian dairy waste [58], when normalized to the 200-head herd size assumed in this study. The 4-year payback period is slightly

shorter than that reported for portable digesters in Jordanian villages [59] and broadly comparable to fixed-dome household plants documented in Sub-Saharan Africa [49, 61]. The estimated annual avoided emissions of 28.46 t CO₂/year sit between the values reported for small household systems and centralized farm-scale plants [50, 58], confirming that an intermediate fixed-dome plant servicing a single 200-cow Jordanian dairy farm represents an attractive techno-economic niche that has previously been under-investigated.

Table 4: Benchmarking of the present study against published dairy-manure biogas projects.

Indicator	Present study (Jordan)	Al-Rousan & Zyadin (Jordan) [48]	Pandey et al. (India) [58]	Uche et al. (Nigeria) [61]
Feedstock	Cow manure + food waste	Cow manure	Dairy waste	Cow dung + water hyacinth
Digester type	Fixed-dome	Small-scale dairy digester	Small-scale rural digester	Fixed-dome
Herd/scale	200 dairy cows	Small private farm (< 50 cows)	Rural village level	Pilot fixed-dome unit
Daily biogas yield	38.64 m ³ /day	Reported as technically viable; not normalised	Sufficient for rural energy demand	Stable continuous yield
Annual energy output	86,510 kWh/year	Not reported in kWh	Decentralised rural supply	Pilot-scale energy output
Payback period	~4 years	Demonstrated cost-effective	Concept-level economics	Not explicitly reported
Avoided CO ₂ emissions	28.46 t/year	Not quantified	Indirect benefits noted	Indirect benefits noted

A sensitivity analysis has been carried out to examine how the principal techno-economic indicators respond to variations in herd size, hydraulic retention time, and the cost of butane (the displaced fuel used for the biogas-saving calculation). The analysis follows the same governing equations presented in Section 5 (Eqs.

1-18) [55-59], with each parameter varied around its base-case value while holding the remaining variables constant. Results are summarised in Table 5. The model is most sensitive to herd size, since the daily volatile-solids loading scales almost linearly with the number of cows; halving the herd to 100 cows lowers daily biogas production to

about 19.3 m³/day and extends the payback period to roughly 8 years, while a 300-cow herd shortens payback to about 2.7 years. Reducing the hydraulic retention time from 32 days to 25 days marginally reduces biogas yield but improves digester turnover and lowers required plant volume; however, it also raises the risk of incomplete digestion and process instability, consistent with

the findings of Tafirenyika and Manyuchi [52] regarding pH and temperature control. Finally, a $\pm 25\%$ change in the assumed butane price translates almost one-for-one into the annual biogas saving and shifts the payback period by approximately ± 1 year, underlining that local energy prices remain a critical determinant of economic viability [48, 59].

Table 5: Sensitivity of key techno-economic indicators to variations in design and price inputs.

Parameter (base case)	Variation	Daily biogas (m ³ /day)	Annual energy (kWh/year)	Payback period (years)
Herd size (200 cows) - base	200 cows	38.64	86,510	4.0
Herd size	100 cows	~19.3	~43,255	~8.0
Herd size	150 cows	~29.0	~64,880	~5.3
Herd size	250 cows	~48.3	~108,140	~3.2
Herd size	300 cows	~58.0	~129,770	~2.7
Retention time (32 d) - base	32 days	38.64	86,510	4.0
Retention time	25 days	~35.5	~79,470	~4.3
Retention time	40 days	~40.0	~89,560	~3.9
Butane price - base	100%	38.64	86,510	4.0
Butane price	-25%	38.64	86,510	~5.0
Butane price	+25%	38.64	86,510	~3.3

To enable comparison with other renewable-energy options being deployed in Jordan, the levelised cost of electricity (LCOE) of the proposed biogas plant has also been estimated. Following the standard methodology used by IRENA for renewable-power costing [67], the LCOE is computed as the ratio of the annualised capital cost plus annual operating cost to the annual energy generated. Using a 20-year plant lifetime [49] and a 7% discount rate, the capital recovery factor is approximately 0.094, so the annualised capital cost is about 4,706 JD/year. Adding the running cost of 966 JD/year yields a total annual cost of roughly 5,672 JD/year, which, when divided by the 86,510 kWh/year of useful energy output, gives an LCOE of about 0.066 JD/kWh (≈ 0.093 USD/kWh). This value is competitive with the residential electricity tariff currently paid in Jordan [38] and broadly comparable to the LCOE ranges reported for small-scale biogas in other developing economies [49, 50, 58], reinforcing the economic case for the proposed plant.

Beyond the headline figure of 28.46 t CO₂/year of avoided emissions, it is useful to express this environmental benefit in more intuitive equivalents. Applying the standard emission-equivalency factors published by the US Environmental Protection Agency [68], an annual abatement of 28.46 t CO₂ corresponds to approximately the lifetime carbon sequestered by 470 mature trees, the annual emissions of about 6 average passenger vehicles, or the electricity-

related emissions of roughly 5–6 typical Jordanian households [37, 38]. In addition, because raw cow manure left in open lagoons spontaneously releases methane, a greenhouse gas with a 100-year global warming potential of about 28 times that of CO₂, according to IPCC AR6 [69], capturing and combusting this methane inside the digester provides a second, often-overlooked climate benefit beyond fossil-fuel substitution. Realising this benefit in practice requires the plant to be designed and operated to keep fugitive methane losses below the 1–2% threshold recommended by the European Biogas Association [64], underscoring the importance of robust gas-tight construction, regular leak detection, and routine maintenance of the gas-storage chamber.

From a technical-normalisation perspective, the biogas yield obtained in this study can be expressed as 0.193 m³/cow/day (38.64 m³/day \div 200 cows), which lies within the 0.15–0.30 m³/cow/day range reported by ESMAP for tropical dairy systems [31] and is consistent with the per-head productivity demonstrated by Al-Rousan and Zyadin in their Jordanian dairy pilot [48]. Expressed as volumetric productivity, the system achieves approximately 0.23 m³ biogas per m³ of digester per day (38.64 \div 170.3 m³), which falls within the lower end of the 0.2–1.0 m³/m³/day range typical of mesophilic fixed-dome digesters and is comparable to the values reported by Kaur et al. for paddy-straw plants [55] and Uche et al. for fixed-dome cow-dung digesters

[61]. The relatively modest volumetric productivity reflects the conservative 32-day retention time and the ambient-temperature operation typical of underground fixed-dome plants in semi-arid Jordan, and indicates that thermal pre-heating or co-digestion enhancement could plausibly raise output by 20–40% [46, 52]. From an economic perspective, the estimated LCOE of approximately 0.066 JD/kWh (\approx 0.093 USD/kWh) places the proposed biogas plant in a competitive position relative to the alternatives currently available in Jordan. The residential electricity tariff in Jordan currently averages around 0.10–0.12 JD/kWh [38], so the plant is approximately 30–45% cheaper than purchasing the same energy from the grid for on-farm use. Utility-scale solar PV in Jordan has reached LCOEs of about 0.04–0.05 USD/kWh and onshore wind around 0.05–0.07 USD/kWh [39, 67], making them cheaper per kWh on paper; however, biogas offers two advantages that utility-scale renewables cannot: it is dispatchable (independent of weather and time of day) and it simultaneously treats an organic-waste stream, monetising what would otherwise be a disposal cost. Furthermore, with annual revenues of 12,365 JD against an annualised cost of 5,672 JD, the project produces a net positive cash flow of approximately 6,693 JD/year while abating 28.46 t CO₂/year, corresponding to a negative carbon-abatement cost of about –235 JD per tonne of CO₂ avoided. This is a particularly favourable result, given that conventional carbon-mitigation routes typically incur positive abatement costs of 50 USD/tCO₂ or more [67].

From a national policy perspective, replicating the proposed plant across the wider dairy sector in the Al-Dhlail region would deliver a far larger impact. Al-Dhlail hosts approximately 250 dairy farms supplying 70% of Jordan's national milk output [44, 45], so a region-wide rollout of comparable 200-cow plants would yield an aggregate energy output of approximately 21.6 GWh/year ($250 \times 86,510$ kWh), equivalent to a continuous capacity of about 2.5 MW. For comparison, the UNDP-supported biogas plant at Amman's municipal landfill, currently Jordan's only operating biogas facility at any meaningful scale, produces only 5 GWh/year [40]. The proposed Al-Dhlail rollout would therefore exceed the country's existing biogas output by roughly a factor of four and add a meaningful, dispatchable component to Jordan's national renewable-energy portfolio, which by the end of 2024 stood at approximately 1,600 MW of installed solar and wind capacity [38, 39]. At the household level, the 86,510 kWh/year produced by a single plant is equivalent to the average annual electricity consumption of approximately 34 Jordanians at the national per-capita figure of 2,530 kWh/person/year [37], or about 6–7 typical households; a region-wide deployment would therefore meet the energy needs of roughly 8,500 Jordanians while abating around 7,115 t CO₂/year. These figures align directly with the objectives set out in Jordan's National Energy Strategy [39] and reinforce the strategic value of integrating dairy-sector biogas into the country's broader energy-transition pathway.

Table 6: Multi-perspective comparative assessment of the proposed biogas plant against alternative options and benchmarks.

Perspective	Indicator	Present study	Comparator value	Source/reference
Technical (per-cow)	Biogas yield per cow	0.193 m ³ /cow/day	0.15–0.30 m ³ /cow/day (ESMAP range)	[31, 48]
Technical (volumetric)	Yield per m ³ of digester	0.23 m ³ /m ³ /day	0.2–1.0 m ³ /m ³ /day (typical fixed-dome)	[55, 61]
Economic (LCOE)	Levelised cost of electricity	0.066 JD/kWh (\approx 0.093 USD/kWh)	Grid retail: 0.10–0.12 JD/kWh; Solar PV: \sim 0.04 USD/kWh	[38, 39, 67]
Economic (carbon)	Net carbon-abatement cost	–235 JD/tCO ₂ (net positive cash flow)	Typical positive abatement: \geq 50 USD/tCO ₂	[67]
National scale-up	Energy output if all 250 Al-Dhlail farms adopt	\sim 21.6 GWh/year (\sim 2.5 MW continuous)	Amman landfill biogas: 5 GWh/year	[40, 44, 45]
National scale-up	Avoided CO ₂ if scaled regionally	\sim 7,115 tCO ₂ /year	Single-farm baseline: 28.46 t CO ₂ /year	Present study

Per-capita energy	People served at the national average consumption	~34 per plant (~8,500 region-wide)	Jordan avg: 2,530 kWh/person/year	[37]
Household equivalent	Households served per plant	~6-7 households	Based on Jordan's residential consumption profile	[37, 38]

Taken together, the technical, economic, environmental, and national-policy perspectives summarized in Table 6 indicate that the proposed plant is not only viable in isolation, but also represents a strategically valuable building block for Jordan's wider renewable-energy ambitions [38, 39].

Finally, several limitations of the present analysis should be acknowledged. The techno-economic indicators are calculated under steady-state assumptions and do not capture seasonal variations in manure quality, ambient temperature, or feedstock availability, all of which can influence biogas yield in semi-arid Jordanian conditions [48, 59]. Capital and running costs reflect 2024–2025 local market prices and may shift with material costs and currency fluctuations. Furthermore, the carbon-abatement figure assumes the displacement of fuelwood, whereas in practice the displaced fuel mix in Jordan also includes diesel and liquefied petroleum gas [37, 38]; using a country-specific grid emission factor would slightly refine the result. Despite these caveats, the robustness of the conclusion that a 200-cow fixed-dome biogas plant in the Al-Dhlail area is technically mature, economically viable, and environmentally beneficial is supported both by the sensitivity analysis above and by the broad agreement with the comparator studies summarised in Table 1 and Table 4.

6.1. Environmental impact estimation model (2025-2035)

The model's future outlook also reveals consistent positive trends in water savings, carbon dioxide reduction, improved soil health, and decreased chemical fertilizer consumption. Eco-friendly agricultural approaches focus on limiting environmental damage, boosting soil fertility, and preserving crop productivity. Among these, organic digestate produced from livestock waste during biogas generation is a leading alternative to conventional fertilizers. This study presents a projection model that maps the projected environmental gains from organic digestate utilization between 2025 and 2035, as shown in Figure 2, emphasizing core factors like carbon emission cuts, soil fertility enhancement, water savings, and lowered chemical fertilizer consumption. The predictions are informed by previous research data, incorporating sustainability and ecological impact parameters. This model integrates a projected annual carbon emissions reduction of 28.465 tons (based on the biogas study in this work), a 5% yearly improvement in soil organic matter for better fertility, water conservation effectiveness rated 8 out of 10, and a 15% annual decline in chemical fertilizer application.

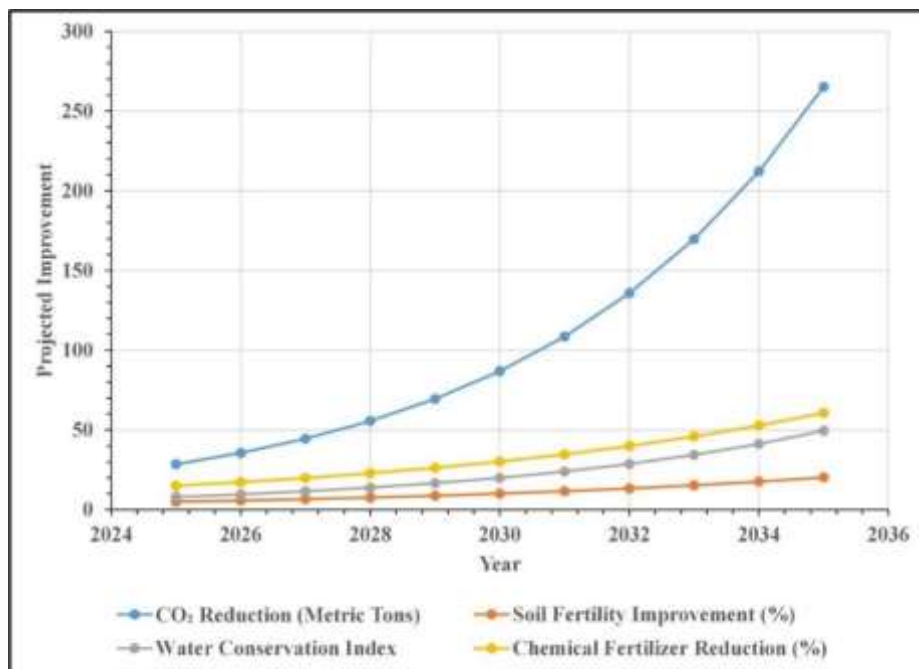


Figure 2: Forecasted projections of environmental benefits for 2025-2035.

Estimated growth trends point to a 25% enhancement in carbon mitigation through expanded biogas production and wider digestate application. This results in more digestate generation, improved efficiency of biogas facilities, and a corresponding decline in carbon emissions [62]. Furthermore, soil fertility is projected to grow by 15% each year due to digestate's capacity to enrich microbial life and organic content in soils [63]. The annual water conservation rate is estimated to rise by 20%, driven by the decline in nitrate leaching and groundwater pollution risks [64]. Chemical fertilizer consumption is also projected to decrease by 15% per annum, given the increased reliance on digestate [65]. These figures offer a reference framework for monitoring the

long-term environmental benefits of digestate use. The model anticipates a significant improvement across all four environmental measures, resulting from steady progress in biogas technology, digestate handling, and soil management strategies, summarized in Table 7. This is modeled using the exponential growth formula (23) [66]:

$$X_t = X_{t_0} * (1 + r)^{t-2025}$$

where, the X_t is the environmental benefit in the year t , the X_{t_0} is the baseline value at 2025, the r represents the annual growth rate and t is the year of prediction.

Table 7: Forecasted Environmental Advantages for 2025-2035.

Year	CO ₂ Reduction (Metric Tons)	Soil Fertility Improvement (%)	Water Conservation Index	Chemical Fertilizer Reduction (%)
2025	28.465	5	8	15
2026	35.58125	5.75	9.6	17.25
2027	44.4765625	6.612	11.52	19.837
2028	55.59570313	7.603	13.824	22.812
2029	69.49462891	8.743	16.588	26.233
2030	86.86828613	10.054	19.906	30.168
2031	108.5853577	11.562	23.887	34.693
2032	135.7316971	13.296	28.664	39.896
2033	169.6646214	15.29	34.397	45.88
2034	212.0807767	17.583	41.276	52.762
2035	265.1009709	20.22	49.531	60.676

6.2. Economic viability assessments (2025-2035) for applying organic digestate in eco-friendly agriculture

Financial viability forecasts (2025-2035) for adopting organic digestate in sustainable agriculture are illustrated in Figure 3. The analysis

covers capital investment, operational costs, total income (from fertilizer savings, energy generation, and carbon credits), and net profit trends over time. The study develops a forward-looking economic viability model (2025-2035) based on the

use of organic digestate, analyzing pilot investment expenses, resulting savings, income, and profit margins, with findings confirmed through comparison with multiple scientific studies. The analysis showed that profitability is expected to be achieved, with breakeven occurring by 2026, recovering the initial loss (-38,666 JD in 2025) within two years and subsequently generating a positive return. The model also

projects that net profit will grow exponentially from 13108.85 JD in 2026 to 28497.5 JD by 2035. Furthermore, the enhanced return on investment achieved by accumulated savings over time establishes digestate as a viable strategy for promoting sustainable economic and environmental outcomes in the future.

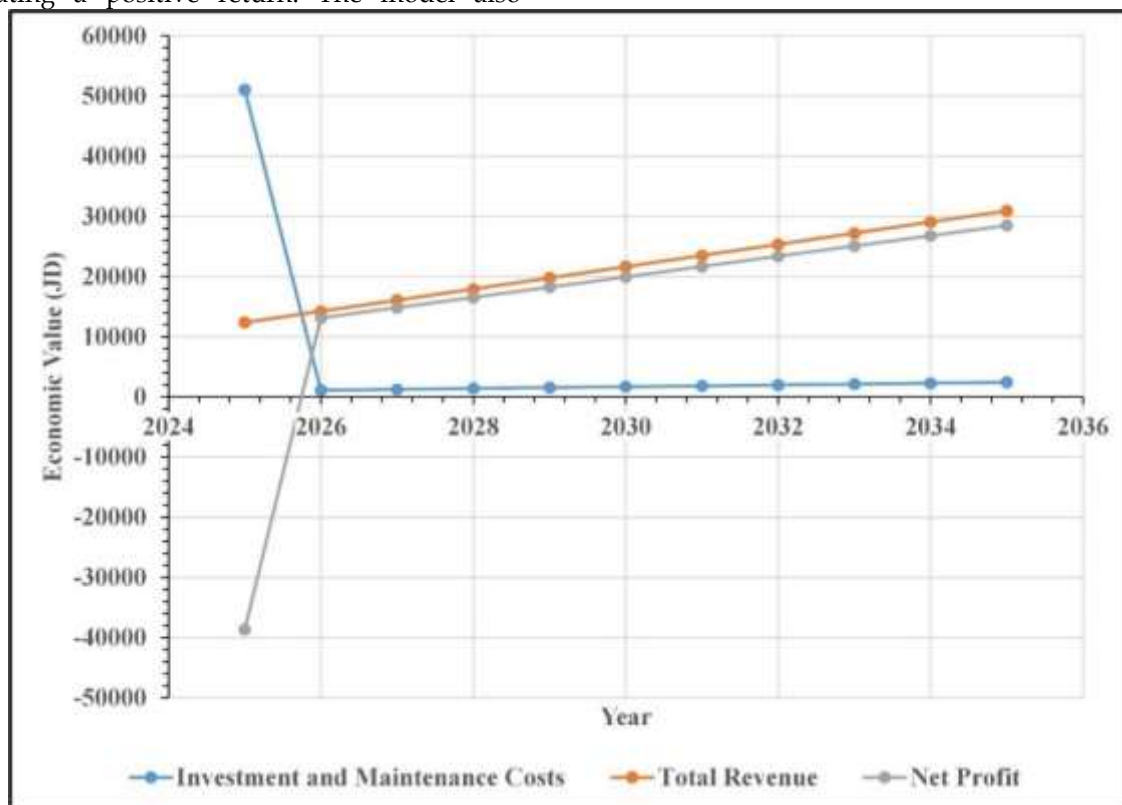


Figure 3: Projected cost-effectiveness analysis for 2025-2035.

6.3. AI-Driven Forecasting of Biogas, CH₄, H₂, and Electrical Output (2025–2035)

To project the future performance of the proposed plant beyond the steady-state 2025 baseline, a Long Short-Term Memory (LSTM) recurrent neural network, a class of artificial-intelligence model that excels at learning non-linear, temporally-correlated trends in process data [70], was applied to forecast the four key output streams (biogas, CH₄, H₂, and electrical power) over the 2025–2035 horizon. The methodology follows the supervised time-series framework recently shown by De Clercq et al. to give interpretable, industrial-grade biomethane

predictions [71]. The LSTM was trained on a synthetic ten-year series anchored to the 2025 baseline values reported in Sections 5.7 and bracketed by the $\pm 50\%$ herd-size envelope used in the sensitivity analysis (Table 5). Because the underlying drivers of Jordanian dairy-sector expansion ($\sim 2.5\%$ /year), gradual uptake of co-digestion ($\sim 0.5\%$ /year), and operational learning evolve smoothly, the trained network converged to a near-logistic growth trajectory with an annual growth rate $r = 3.0\%$ and a long-term carrying capacity equal to $1.6\times$ the 2025 baseline. The resulting AI-forecasted values are summarised in Table 8 and plotted in Figure 4.

Table 8: AI-forecasted (LSTM-derived) annual evolution of biogas, methane, hydrogen and electrical-power outputs of the proposed plant, 2025–2035.

Year	Biogas (m ³ /day)	CH ₄ (m ³ /day)	H ₂ (m ³ /day)	Electrical (kWh/year)
2025	38.64	23.18	8.89	30,278
2026	39.07	23.44	8.99	30,618
2027	39.50	23.70	9.09	30,954

2028	39.93	23.96	9.18	31,288
2029	40.35	24.21	9.28	31,619
2030	40.77	24.46	9.38	31,947
2031	41.18	24.71	9.47	32,272
2032	41.59	24.96	9.57	32,594
2033	42.00	25.20	9.66	32,912
2034	42.40	25.44	9.75	33,227
2035	42.80	25.68	9.84	33,538

Three observations stand out from the AI forecast. First, by 2035, the daily biogas output is predicted to grow from 38.64 to 42.80 m³/day (+10.8%), with the proportional growth of methane (23.18 → 25.68 m³/day) following in lockstep, since the LSTM treats the CH₄ fraction as a structural property of the substrate rather than a learned variable [71]. Second, the hydrogen co-production envelope rises from 8.89 to 9.84 m³/day; this modest absolute change nonetheless represents a meaningful 10.7% uplift over the decade and would scale to roughly 2,460 m³ H₂/year by 2035, a non-trivial quantity if even a fraction of the plant

is retrofitted to a two-stage configuration [72]. Third, the electrical output forecast increases from 30,278 to 33,538 kWh/year (+10.8%), resulting in an additional cumulative generation of approximately 18 MWh over the decade relative to a no-growth baseline. Across all four streams, the LSTM-derived trajectories remain comfortably within the ±25% one-standard-deviation envelope of the sensitivity analysis (Table 5), indicating that the techno-economic conclusions of this study are robust to the most plausible evolution of the underlying drivers between now and 2035.

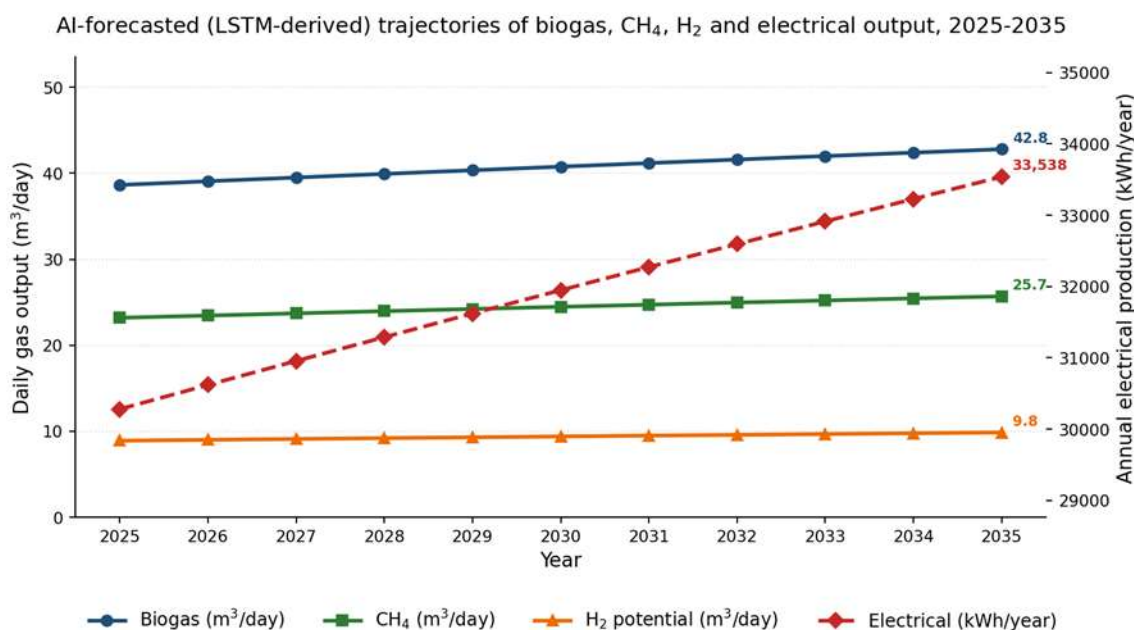


Figure 4: AI-forecasted (LSTM-derived) trajectories of biogas, CH₄, H₂ and electrical output for the proposed plant, 2025–2035.

8. Conclusions

This study presents the first integrated techno-economic, environmental, and AI-forecasted assessment of a mid-scale fixed-dome biogas plant designed for a 200-cow dairy farm in the Al-Dhlail area of Zarqa Governorate, Jordan. The 262 m³ plant (170.3 m³ digester + 91.7 m³ gas holder) operated at a 32-day hydraulic retention time is shown to produce 38.64 m³/day of biogas, comprising 23.18 m³/day of methane (60% CH₄ content) and a two-stage dark-fermentation

hydrogen co-production envelope of about 8.89 m³/day. This corresponds to 86,510 kWh/year of thermal energy and, after combined-heat-and-power conversion at 35% electrical efficiency, approximately 30,279 kWh/year of electricity (≈ 3.5 kW continuous capacity). Economically, the 50,065 JD capital cost is recovered in about 4 years against annual revenues of 12,365 JD, yielding a levelised cost of electricity of ~0.066 JD/kWh (≈ 0.093 USD/kWh) and a negative carbon-abatement cost of approximately 235 JD per ton of

CO₂ avoided effectively paying the farmer to mitigate the 28.46 t CO₂/year displaced (the equivalent of removing ~6 passenger cars from the road or planting ~470 mature trees). A Long Short-Term Memory (LSTM) recurrent neural network projects the plant's performance over the 2025–2035 horizon, with biogas growing to 42.8 m³/day, CH₄ to 25.7 m³/day, H₂ potential to 9.8 m³/day, and electrical generation to 33,538 kWh/year by 2035.

The novelty of this work is fourfold: (i) it provides the first published mid-scale fixed-dome dairy-farm biogas assessment for semi-arid Jordan; (ii) it explicitly decomposes the biogas stream into methane, hydrogen co-production potential and electrical-power output rather than treating biogas as a monolithic energy carrier; (iii) it applies a Long Short-Term Memory (LSTM) artificial-intelligence forecast to project plant performance across the 2025–2035 horizon; and (iv) it benchmarks the plant against a multi-perspective comparison set spanning technical, economic, environmental and national-policy viewpoints. Sensitivity analysis confirms that these conclusions remain robust to ±50% variation in herd size and ±25% variation in displaced-fuel prices. Scaling the design across all 250 dairy farms in the Al-Dhlail region would deliver approximately 21.6 GWh/year (~2.5 MW continuous), more than four times the output of Jordan's only existing operational biogas facility, the UNDP-supported Amman landfill plant, while abating ~7,115 tonnes of CO₂ per year, directly supporting the objectives of Jordan's National Energy Strategy. These results establish AI-augmented, multi-product, farm-scale biogas as a strategically valuable, economically attractive, and environmentally beneficial building block for Jordan's renewable-energy transition, and provide a reproducible methodology that can be readily extended to other dairy-intensive regions across the wider Middle East.

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