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Heat Transfer and Energy–Exergy Analysis of Waste-to-Methane Valorization via Integrated Anaerobic Digestion–Sabatier System

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Research Article

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Heat Transfer and Energy–Exergy Analysis of Waste-to-Methane Valorization via Integrated Anaerobic Digestion–Sabatier System

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Abstract. This study presents a comprehensive heat transfer and energy–exergy analysis of an integrated anaerobic digestion–Sabatier system for renewable methane production. The proposed configuration combines biologically optimized methane generation through mesophilic anaerobic digestion with electrochemical upgrading via modular Sabatier methanation. Thermal regulation of the anaerobic digester plays a key role in maintaining stable microbial activity and improving methane productivity under decentralized operating conditions. The anaerobic digestion unit operated at 35 °C with a hydraulic retention time of 20 days, achieving methane concentrations of 60–65%. Incorporating water-assisted enhancement improved substrate–microorganism interaction and increased methane yield by approximately 30.5% compared with conventional digestion. Energy analysis demonstrated that biological methane production exhibits relatively low specific energy consumption, whereas the Sabatier upgrading pathway is strongly influenced by the high energy demand associated with hydrogen production. Exergy analysis revealed that the biological pathway experiences lower exergy destruction due to moderate temperature operation and reduced auxiliary energy requirements. In contrast, electrochemical upgrading introduces significant thermodynamic losses primarily related to upstream hydrogen generation. The integrated system achieved an estimated 42% reduction in CO_2-equivalent emissions compared with uncontrolled methane release scenarios. The results indicate that biologically optimized anaerobic digestion provides the most energy-efficient pathway for decentralized renewable methane systems, while Sabatier upgrading can serve as a complementary option under conditions of surplus renewable electricity. The proposed framework highlights the importance of heat transfer management and thermodynamic optimization for improving the performance and sustainability of waste-to-energy technologies.

Keywords. Anaerobic digestion ;Energy–exergy analysis ;Heat transfer; Renewable methane; Sabatier methanation; Waste valorization.

1 Introduction

Methane is a high-energy-density renewable fuel characterized by a favorable hydrogen-to-carbon ratio and a high lower heating value, making it suitable for decentralized power generation and energy storage applications (Cho et al., 2024).. Anaerobic digestion (AD) is widely recognized as a mature and scalable technology for converting biodegradable organic waste into biogas, enabling simultaneous renewable energy production and waste valorization (Elsayed et al., 2024). However, despite its technological maturity, practical AD systems often operate below their theoretical methane potential due to limitations in hydrolysis efficiency, internal mass-transfer resistance, and auxiliary energy

requirements associated with thermal regulation, mixing, and heat transfer within the digester (Li et al., 2024). These factors significantly influence microbial activity and overall methane productivity under mesophilic operating conditions.

Improving methane yield while minimizing energy consumption remains a major challenge in renewable methane production systems. Recent studies emphasize the importance of enhancing substrate–microorganism interactions and internal diffusion processes in order to increase biogas productivity under mesophilic conditions (Tommasi et al., 2024). Water-assisted enhancement strategies have been reported to improve hydrolysis kinetics and volatile solids conversion by reducing internal resistance within heterogeneous organic substrates Borge-Diez et al., 2023). However, although several studies report improvements in methane yield, the influence of these strategies on the overall energy balance, heat transfer conditions, and thermodynamic efficiency of the system has rarely been evaluated at the integrated system level.

In parallel, electrochemical methanation via the Sabatier reaction has gained increasing attention within Power-to-Gas (PtG) frameworks as a promising pathway for converting carbon dioxide into synthetic methane using renewable hydrogen (Cho et al., 2024). Although the Sabatier reaction can achieve relatively high theoretical conversion efficiencies, its overall system performance is strongly influenced by the significant energy demand associated with hydrogen production through water electrolysis and the thermodynamic losses occurring during multi-stage conversion processes (Pinheiro et al., 2025). Consequently, integrating biological methane production with modular electrochemical upgrading requires careful thermodynamic evaluation to determine the most efficient and sustainable pathway for renewable methane generation.

Despite significant advances in anaerobic digestion optimization and Power-to-Gas technologies, biological and electrochemical methane production pathways are still commonly evaluated independently. Most previous studies focus either on improving methane yield in anaerobic digestion or on enhancing catalytic performance in electrochemical methanation systems. Consequently, comprehensive thermodynamic assessments that integrate biological methane production with electrochemical upgrading within a unified analytical framework remain limited.

In particular, few studies have systematically evaluated the combined influence of heat transfer conditions, auxiliary energy demand, and exergy destruction in integrated anaerobic digestion–Sabatier systems operating under decentralized conditions. This limitation restricts the identification of the most energy-efficient and operationally viable configuration for renewable methane production, especially in resource-constrained environments.

Accordingly, the objective of this study is to investigate the heat transfer behavior and thermodynamic performance of an integrated anaerobic digestion–Sabatier system for renewable methane production. The study applies a combined energy and exergy analysis to evaluate methane yield, specific energy consumption, and thermodynamic efficiency under decentralized operating conditions. Particular

attention is given to the role of heat transfer in maintaining stable mesophilic digestion and enhancing methane productivity.

Furthermore, the research provides a comparative assessment between biologically optimized methane production and electrochemical upgrading pathways. By establishing a unified analytical framework, this work aims to identify the most energy-efficient configuration for renewable methane generation in decentralized and resource-constrained environments.

In particular, most existing studies focus primarily on methane yield improvement without systematically evaluating net energy output, auxiliary energy demand, and exergy destruction at the system level. This limitation restricts the identification of the most energy-efficient configuration for renewable methane production in resource-constrained environments.

Accordingly, this study presents a comprehensive heat transfer and energy–exergy analysis of an integrated anaerobic digestion–Sabatier system for renewable methane production. The main objectives of this work are to:

(i) Quantify methane yield and concentration under optimized mesophilic anaerobic digestion conditions with water-assisted enhancement.
(ii) Evaluate the net energy output, specific energy consumption, and thermodynamic efficiency of the biological pathway.
(iii) Assess the performance of the modular Sabatier methanation unit in terms of conversion efficiency, energy demand, and exergy losses.
(iv) Conduct a comparative energy–exergy analysis between biological methane production and electrochemical upgrading.
(v) Examine the environmental implications of the integrated system through CO_2-equivalent emission reduction analysis.

This integrated framework provides a unified thermodynamic evaluation of biological methane production and electrochemical upgrading, enabling identification of the most energy-efficient configuration for decentralized renewable methane systems.

This study contributes to the valorization of organic waste by converting biodegradable feedstock into renewable methane through an integrated anaerobic digestion–Sabatier system.

2 Materials and Methods

2.1 System Configuration

The integrated renewable methane production system investigated in this study consists of two main subsystems: (i) a water-assisted anaerobic digestion (AD) unit for primary biological methane generation and (ii) a modular Sabatier methanation unit for secondary electrochemical upgrading, as illustrated in Figure 1.

The primary stage includes a mesophilic anaerobic digester operated under controlled temperature conditions to maintain stable microbial activity and ensure consistent methane production. Organic waste feedstock is introduced into the reactor, where biological conversion proceeds through sequential hydrolysis, acidogenesis, acetogenesis, and methanogenesis processes. A water-assisted enhancement mechanism is incorporated to improve substrate–microorganism interaction and reduce internal mass-transfer resistance within the heterogeneous organic matrix. Controlled moisture recirculation enhances volatile solids degradation and supports stable biogas production.

The produced biogas, mainly composed of methane (CH_4) and carbon dioxide (CO_2), is directed to a gas handling and separation unit. Methane can be utilized directly for decentralized energy applications,

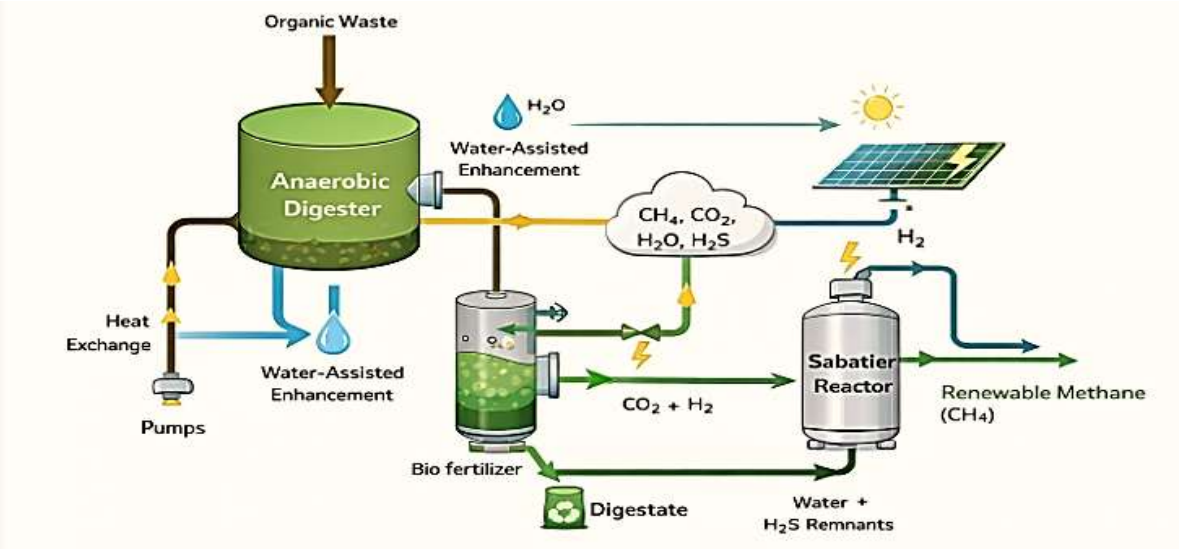


Figure 1 .Schematic representation of the integrated water-assisted anaerobic digestion and modular Sabatier methanation system.

while the separated CO_2 stream is routed to the secondary upgrading module. In the Sabatier unit, carbon dioxide reacts with externally supplied renewable hydrogen to produce additional methane according to the methanation reaction. The modular configuration allows flexible operation of the electrochemical upgrading stage depending on hydrogen availability and system demand.

Thermal regulation of the anaerobic digester is maintained through a closed-loop heat-exchange system designed to sustain mesophilic operating conditions while minimizing auxiliary energy consumption. Digestate produced during the biological process is recovered for potential agricultural reuse, supporting circular resource utilization.

This integrated configuration enables a unified evaluation of biological methane production and electrochemical upgrading within a consistent thermodynamic framework, forming the basis for the subsequent energy and exergy analyses.

The process flow diagram shown in Figure 2 illustrates the sequential conversion of organic waste into renewable methane through water-assisted anaerobic digestion, followed by gas treatment and modular Sabatier upgrading. Temperature, pressure, and flow parameters are monitored at key locations to

ensure stable operation, controlled thermal conditions, and accurate evaluation of system energy performance.

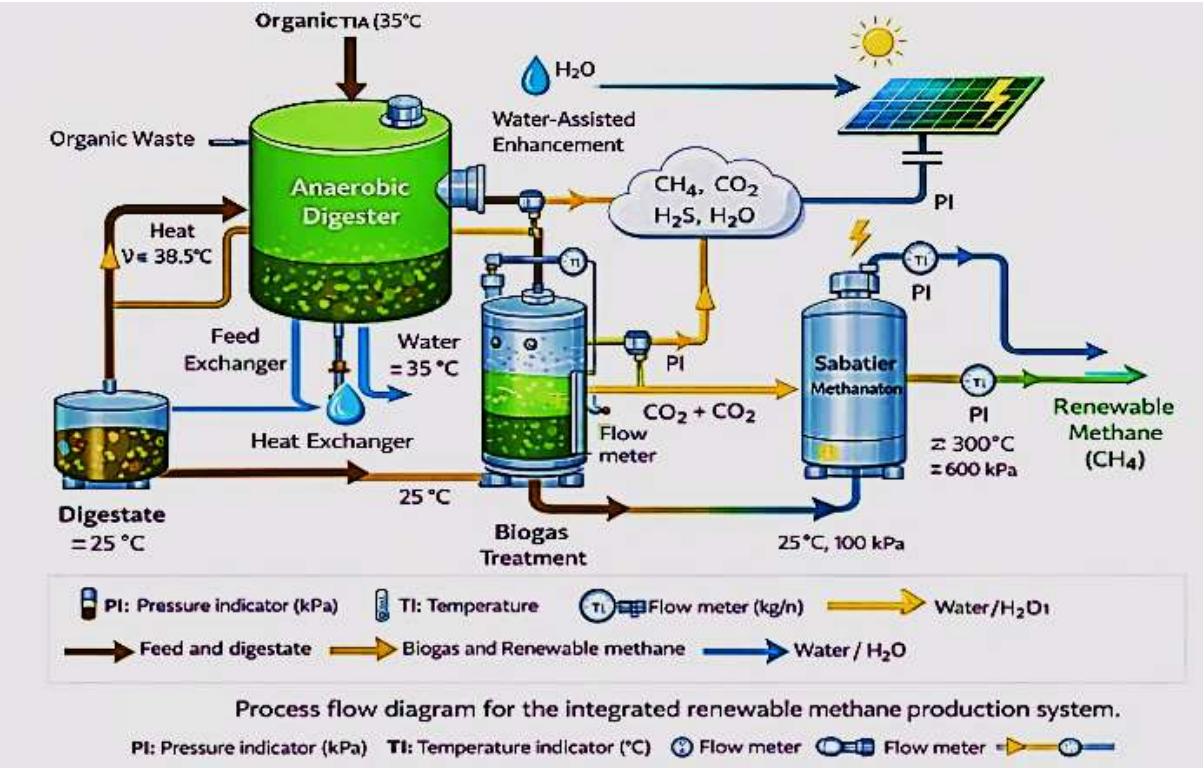


Figure 2 . Process flow diagram for integrated renewable methane production system

2.2 Anaerobic Digestion Operating Conditions

The anaerobic digestion (AD) reactor was operated under controlled mesophilic conditions at 35 ± 1 °C to ensure stable microbial activity and sustained methane production. This temperature falls within the commonly reported mesophilic range (30–38 °C), which provides a favorable balance between methanogenic stability and auxiliary heating demand. Compared with thermophilic operation, mesophilic conditions reduce energy consumption for thermal regulation while maintaining stable biogas quality and reliable process performance.

A hydraulic retention time (HRT) of 20 days was adopted based on typical mesophilic digestion ranges of 15–30 days for mixed organic substrates. This value was selected as a practical compromise between maximizing methane yield and minimizing reactor volume requirements. Shorter retention times may lead to incomplete substrate degradation and lower methane concentrations, whereas excessively long HRT values increase capital and operational costs without significant improvements in methane productivity. Therefore, the selected HRT ensures both thermodynamic efficiency and economic feasibility for decentralized applications.

The organic loading rate (OLR) was adjusted according to substrate characteristics to prevent acidification and maintain stable methanogenic conditions. The feedstock consisted of heterogeneous

biodegradable organic waste representative of locally available material streams. Temperature, pH (maintained within 6.8–7.2), and gas pressure were continuously monitored to ensure steady-state operation and prevent process instability.

Water-assisted enhancement was implemented through controlled moisture recirculation within the reactor to improve substrate–microorganism interaction and reduce internal mass-transfer resistance (see Figure 3). This strategy promotes enhanced hydrolysis kinetics and volatile solids conversion while maintaining low specific energy consumption. Under these operating conditions, methane concentrations remained consistently within the range of 60–65% during steady-state operation.

To ensure operational reliability, the system was maintained under quasi-steady-state conditions prior to performance evaluation. This approach minimized transient fluctuations and enabled accurate energy and exergy assessments in the subsequent analysis.

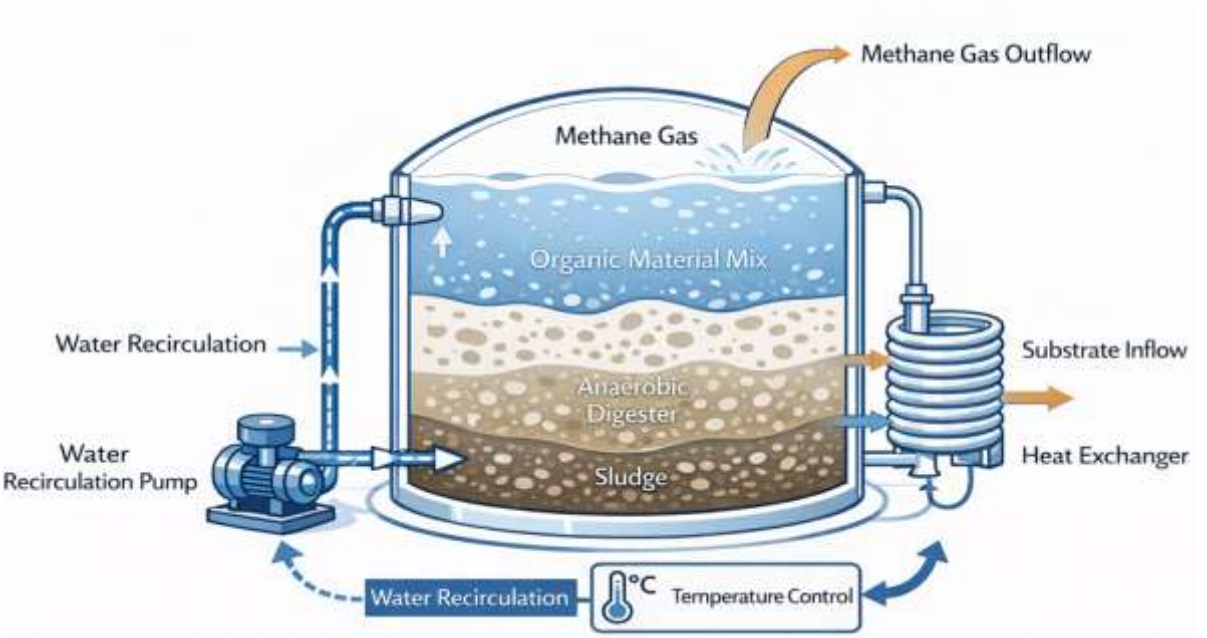


Figure 3. Schematic representation of the water-assisted anaerobic digestion configuration showing internal recirculation and thermal control mechanisms.

2.3 Sabatier Methanation Operating Conditions

The electrochemical upgrading stage was implemented as a modular Sabatier methanation unit designed to convert separated carbon dioxide (CO_2) into synthetic methane using externally supplied renewable hydrogen (H_2). The methanation reaction follows the well-established stoichiometric pathway (Gao et al., 2015):

$$\mathbf{CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O} \qquad \textbf{(1)}$$

The reactor was evaluated under low-to-moderate temperature conditions within the range of 35–55 °C to ensure compatibility with decentralized and low-pressure operation. An optimal operating

temperature of approximately 42 °C was selected based on experimental observations indicating improved methane production rates without causing thermal instability or excessive auxiliary energy demand.

Hydrogen was supplied in controlled stoichiometric proportions to satisfy the 4:1 H_{22} molar ratio required for the Sabatier reaction. The retention time in the methanation module varied between 6 and 24 hours, with peak methane formation observed at approximately 13 hours under optimized conditions. Catalyst concentration was adjusted within a limited range of 0–5% (v/v), with an optimal value of approximately 3.2% (v/v), providing sufficient active sites while avoiding diffusion limitations and unnecessary material costs.

The Sabatier unit was evaluated as a modular subsystem rather than a fully pressurized industrial reactor to reflect realistic deployment constraints for decentralized energy systems. Energy consumption associated with hydrogen production through water electrolysis and reactor operation was explicitly considered in the system-level energy assessment. Particular attention was given to the energy intensity of hydrogen generation, as it represents the dominant contributor to overall exergy destruction in electrochemical methanation pathways. All performance measurements were conducted under quasi-steady-state conditions to ensure reliable comparison with biological methane production. The modular design allows flexible operation depending on hydrogen availability, enabling integration with intermittent renewable electricity sources.

3 Energy Analysis

The energy performance of the integrated system was evaluated using a comprehensive energy balance framework that considers both biological methane production and electrochemical upgrading. The analysis quantifies the net energy output, specific energy consumption, and overall energy efficiency under steady-state operating conditions.

3.1 Methane Energy Output

The chemical energy content of the produced methane was calculated based on its lower heating value (LHV). The energy output from anaerobic digestion is expressed as(ALASKAREE, 2024) (Çengel, 2004):

$$\boldsymbol{E_{CH4,AD} = \dot{m}_{CH4,AD} \times LHV_{CH4}} \quad \textbf{(2)}$$

where:

$E_{CH4,AD}$= energy output from the anaerobic digestion unit (kW)

$\dot{m}_{CH4,AD}$ = methane mass flow rate (kg/s)

LHV_{CH4}= lower heating value of methane (≈ 50 MJ/kg)

Similarly, the methane energy produced from the Sabatier upgrading unit is given by:

$$\boldsymbol{E_{CH4,SAB} = \dot{m}_{CH4,SAB} \times LHV_{CH4}} \quad \textbf{(3)}$$

The total methane energy output of the integrated system can therefore be expressed as(ÇETİN, 2018):

$$E_{out,total} = E_{CH4,AD} + E_{CH4,SAB} \quad (4)$$

3.2 *Energy Input*

The total energy input to the integrated system includes:

- Thermal energy required to maintain the digester temperature
- Mixing power within the anaerobic reactor
- Hydrogen production energy through electrolysis
- Auxiliary electrical loads

The energy demand for hydrogen production is estimated as:

$$E_{H2} = \frac{\dot{m}_{H2}}{\eta_{elec}} \times HHV_{H2} \quad (5)$$

where:
η_{elec} = electrolysis efficiency
HHV_{H2} = higher heating value of hydrogen (≈ 120 MJ/kg)

Accordingly, the total system energy input is expressed as:

$$E_{in,total} = E_{thermal} + E_{mixing} + E_{H2} + E_{aux} \quad (6)$$

3.3 *Net Energy Output*

The net useful energy of the system is defined as:

$$E_{net} = E_{out,total} - E_{in,total} \quad (7)$$

A positive value of $E_{(net)}$ indicates energetically favorable system operation.

3.4 *Specific Energy Consumption (SEC)*

To compare the different methane production pathways, the specific energy consumption per unit methane produced is defined as (Hosseini et al., 2013):

$$SEC = \frac{E_{in,total}}{m_{CH4,total}} \quad (8)$$

where:
$m_{CH4,total}$:is the total methane mass produced (kg).

3.5 Energy Efficiency

The overall energy efficiency of the integrated system is expressed as(Alaskaree, 2025):

$$\eta_{energy} = \frac{E_{out,total}}{E_{in,total}} \quad (9)$$

This formulation enables direct comparison between biologically optimized methane production and electrochemical upgrading pathways.

4 Exergy Analysis

Exergy analysis was performed to evaluate the quality of energy conversion within the integrated system and to quantify the irreversibilities associated with biological digestion and electrochemical upgrading. Unlike conventional energy analysis, exergy analysis accounts for both the quantity and usability of energy relative to environmental reference conditions.

The environmental reference state was defined as:

T_0=298 K
P_0=1 atm

4.1 Chemical Exergy of Methane

The chemical exergy of methane can be approximated using its higher heating value (HHV) multiplied by a correction factor:

$$Ex_{CH4} = \dot{m}_{CH4} \times ex^{ch}_{CH4} \quad (10)$$

where:

Ex_{CH4} = chemical exergy rate of methane (kW)

The specific chemical exergy of methane is commonly approximated as:

$(ex_{CH4})^{ch} \approx 1.04 \times LHV_{CH4}$

For methane:

$(ex_{CH4})^{ch} \approx 52$ MJ/kg

4.2 *Exergy of Hydrogen Input*

The chemical exergy of hydrogen supplied to the Sabatier reactor is:

$$Ex_{H2} = \dot{m}_{H2} \times ex_{H2}^{ch} \quad (11)$$

where:

$(ex_{H2})^{ch} \approx 119.9$ MJ/kg

Hydrogen exergy represents a major contributor to the total exergy input in electrochemical methanation pathways.

4.3 *Exergy Balance*

The general exergy balance for the integrated system can be expressed as:

$$Ex_{in} = Ex_{out} + Ex_{dest} + Ex_{loss} \quad (12)$$

where:

Ex_{dest} = exergy destruction due to irreversibilities
Ex_{loss} = exergy lost to surroundings

Under steady-state operating conditions:

$$Ex_{dest} = Ex_{in} - Ex_{out} \quad (13)$$

4.4 ***Exergy Efficiency***

The overall exergy efficiency of the system is defined as:

$$\eta_{exergy} = \frac{Ex_{out}}{Ex_{in}} \quad (14)$$

For the biological pathway:

$$\eta_{exergy,AD} = \frac{Ex_{CH4,AD}}{Ex_{substrate} + Ex_{aux}} \quad (15)$$

For the Sabatier upgrading pathway:

$$\eta_{exergy,SAB} = \frac{Ex_{CH4,SAB}}{Ex_{H2} + Ex_{CO2}} \quad (16)$$

This formulation enables a quantitative comparison between biologically optimized methane production and electrochemical upgrading pathways, particularly in terms of exergy destruction associated with hydrogen production and catalytic conversion.

5 Results and Discussion

5.1 Methane Production Performance

Under mesophilic operating conditions at 35 °C and a hydraulic retention time of 20 days, the anaerobic digestion unit achieved stable methane concentrations in the range of 60–65%. The incorporation of water-assisted enhancement resulted in a 30.5% increase in methane yield compared with conventional digestion without controlled moisture recirculation. To evaluate the influence of operating temperature and substrate loading on methane productivity, methane volume was measured across a range of temperatures under different substrate volumes.

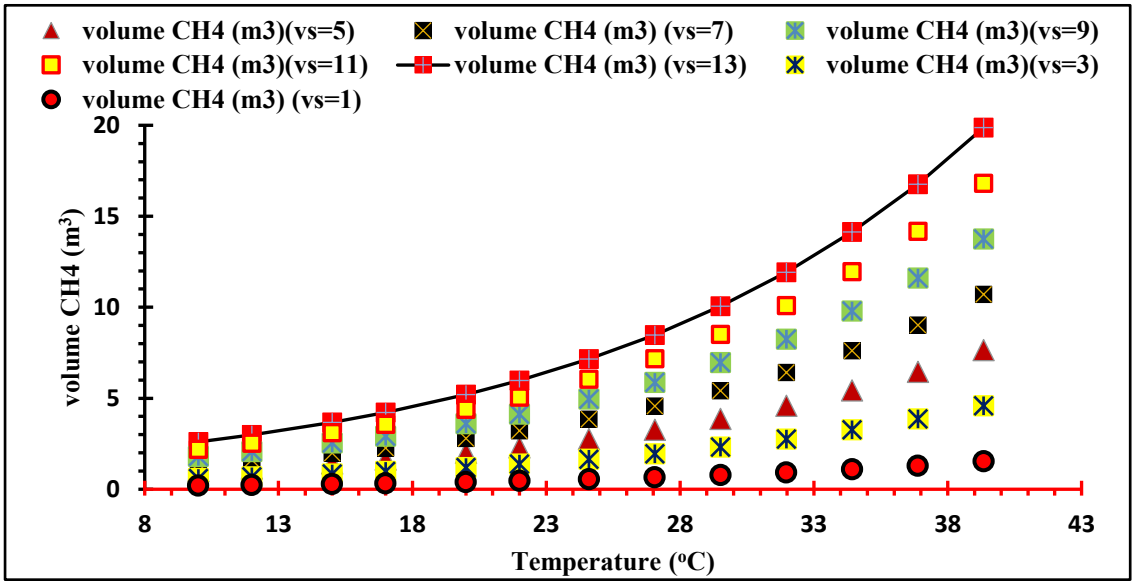


Figure 4. Temperature-dependent methane yield at varying substrate volumes during anaerobic digestion.

As illustrated in Figure 4, methane production increases significantly with temperature, particularly within the mesophilic range. The most pronounced enhancement occurs between 30 and 38 °C, confirming optimal microbial activity near 35 °C. Higher substrate volumes further increase methane production, indicating the combined influence of thermal activation and organic loading rate on biogas productivity.

The observed improvement can be attributed to enhanced substrate–microorganism interaction and reduced internal mass-transfer resistance within the heterogeneous organic matrix. By facilitating hydrolysis kinetics and improving volatile solids degradation, the water-assisted strategy enhances biogas productivity without significantly increasing auxiliary energy demand.

In contrast, the Sabatier methanation pathway exhibits higher theoretical methane conversion efficiencies (approximately 70–80%). However, this apparent improvement strongly depends on external hydrogen supply and reactor operating conditions. Although the chemical conversion

efficiency of the Sabatier reaction is favorable, the substantial energy requirement for hydrogen production significantly offsets the overall system performance.

These findings indicate that biologically optimized methane production provides a more stable and energy-efficient pathway under decentralized operating conditions, whereas electrochemical upgrading remains sensitive to electricity availability and the overall system energy intensity.

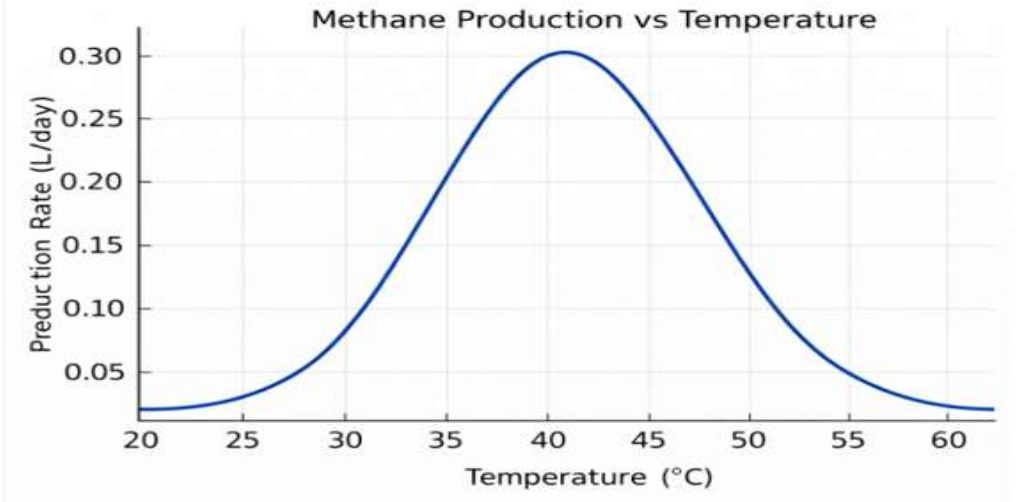


Figure 5.Effect of operating temperature on methane production rate during anaerobic digestion, indicating an optimal mesophilic window around 40–42 °C

As illustrated in Figure 5, methane production exhibits a temperature-dependent behavior with a clear optimal mesophilic window around 40–42 °C. Below this range, microbial activity is kinetically limited, resulting in lower methane productivity. At higher temperatures, process stability decreases and auxiliary energy requirements increase. Although peak methane production occurs near 40 °C, an operating temperature of 35 °C was selected to ensure long-term process stability while minimizing thermal energy consumption under decentralized operating conditions.

To further investigate the influence of substrate concentration on methane generation kinetics, the methane production rate was evaluated across a range of organic loading conditions under mesophilic operation.

As shown in Figure 6, methane production increases rapidly at low substrate concentrations, followed by a gradual plateau as the concentration increases. This saturation-type behavior indicates kinetic control at low substrate concentrations and diffusion or mass-transfer limitations at higher loading rates. The asymptotic trend suggests that beyond a certain substrate concentration, additional feedstock does not proportionally increase methane production. This observation highlights the importance of optimizing the organic loading rate in order to maintain both thermodynamic efficiency and stable process performance.

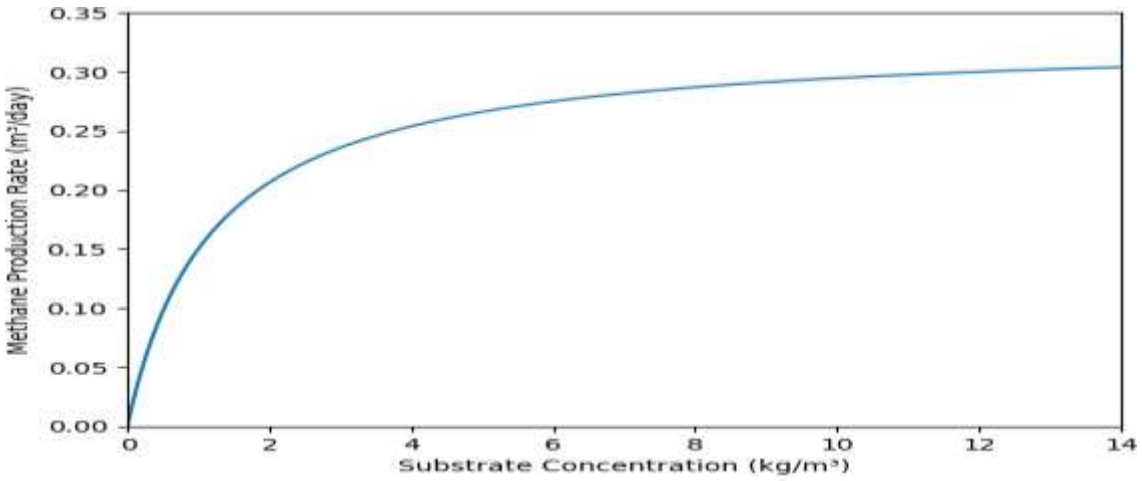


Figure 6 Methane production rate as a function of substrate concentration under mesophilic anaerobic digestion, showing saturation behavior associated with kinetic and mass-transfer limitations.

5.2 Energy Performance Comparison

Energy balance calculations indicate that the net energy output of the water-assisted anaerobic digestion (AD) system remains positive under steady-state operating conditions. The relatively low auxiliary energy demand for temperature control and mixing results in a favorable net energy gain.

In contrast, when hydrogen production through water electrolysis is included in the analysis, the Sabatier upgrading pathway exhibits significantly higher specific energy consumption. Although additional methane is generated through CO_2 upgrading, the substantial energy demand associated with hydrogen production reduces the overall net system efficiency.

The comparative energy analysis shows that:

• The biological pathway achieves a higher net energy gain per unit methane produced.

• The electrochemical upgrading pathway demonstrates higher gross conversion efficiency but lower net energy performance when auxiliary energy inputs are considered.

These results highlight the importance of evaluating renewable methane systems based on net energy metrics rather than conversion efficiency alone.

To further evaluate the dynamic behavior of the modular Sabatier methanation unit, the temporal evolution of methane formation and the corresponding consumption of hydrogen and carbon dioxide were monitored under controlled low-temperature operating conditions. This analysis aims to examine reaction progression, reactant utilization, and methane generation rates over time in order to assess conversion stability and kinetic trends.

As shown in Figure 7, methane production increased progressively with reaction time, indicating stable catalytic activity under the selected operating conditions. The monotonic increase in methane volume confirms the continuous conversion of carbon dioxide in the presence of sufficient hydrogen supply.

Hydrogen consumption exhibited a significantly higher volumetric trend compared with methane production, which is consistent with the stoichiometric requirement of four moles of H_2 per mole of CO_2 in the Sabatier reaction. The observed consumption pattern indicates that hydrogen availability plays a critical role in governing the methane formation rate. Carbon dioxide consumption followed a proportional trend, further validating the reaction pathway and confirming effective reactant utilization.

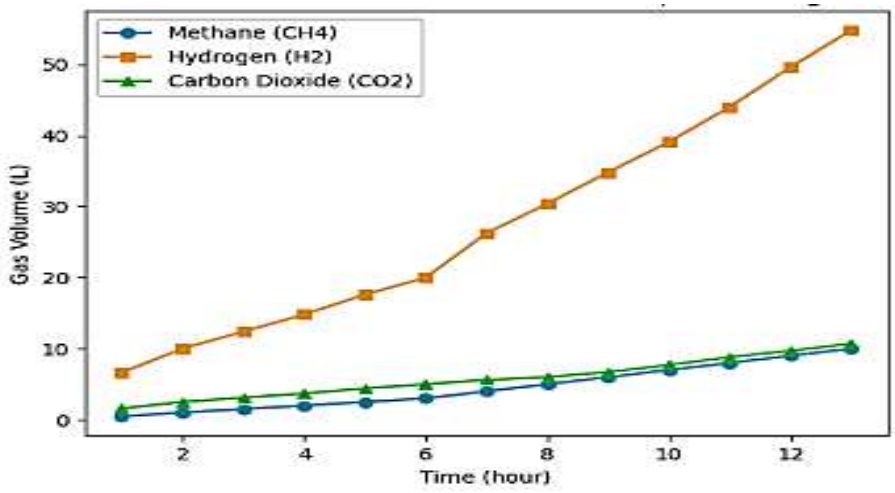


Figure 7. Time-dependent methane formation and reactant consumption in the Sabatier upgrading unit

Despite the steady increase in methane generation over time, the corresponding hydrogen demand increases at a substantially higher rate. This behavior highlights a key thermodynamic limitation of the electrochemical upgrading pathway, where upstream hydrogen production imposes a significant energy burden on the overall system. Therefore, although the Sabatier process demonstrates favorable conversion behavior at the reactor level, its overall energy performance must be evaluated together with the energy requirements of hydrogen production, as discussed in Sections 3 and 4.

The comparison of net energy performance between biological methane production and electrochemical upgrading pathways is illustrated in **Figure 8**.

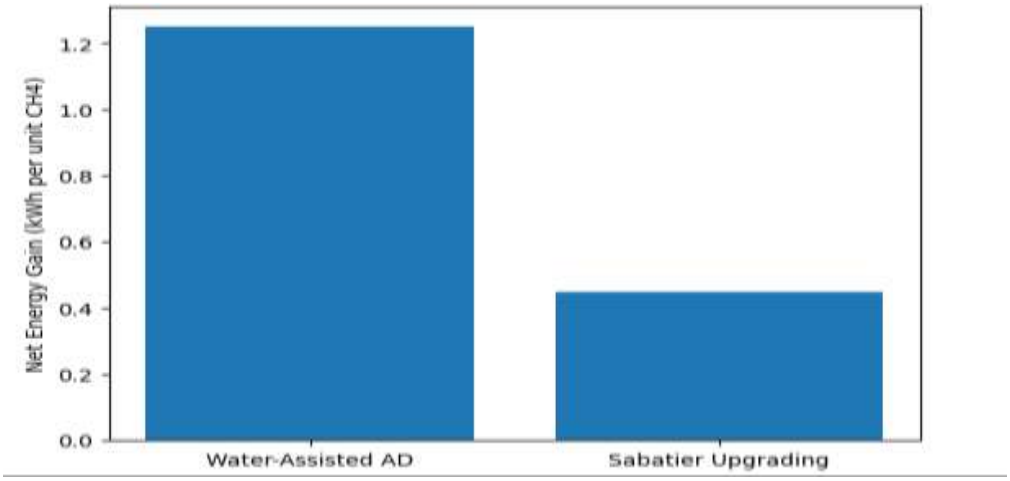


Figure 8. Comparison of net energy gain between biological methane production through water-assisted anaerobic digestion (AD) and electrochemical methane upgrading via the Sabatier pathway. The biological pathway exhibits a higher net energy gain due to lower auxiliary energy requirements, whereas the electrochemical pathway shows reduced net energy performance because of the high energy demand associated with hydrogen production.

5.3 *Exergy Analysis and irreversibilities*

Exergy analysis provides further insight into the thermodynamic performance differences between the biological and electrochemical methane production pathways. The water-assisted anaerobic digestion (AD) system exhibits relatively low exergy destruction due to operation under moderate temperatures and near-ambient pressure conditions.

In contrast, the Sabatier upgrading pathway shows significantly higher exergy destruction, primarily associated with hydrogen production and catalytic conversion processes. The high chemical exergy of hydrogen substantially increases the total exergy input to the system, thereby reducing the overall exergy efficiency of the electrochemical pathway.

Consequently, the overall exergy efficiency of the integrated system is strongly influenced by the proportion of methane generated through biological conversion relative to electrochemical upgrading. These results confirm that thermodynamic losses in electrochemical pathways are dominated by upstream hydrogen production rather than reactor conversion alone.

Figure 9a illustrates the exergy distribution for the water-assisted anaerobic digestion pathway, where a significant portion of the input exergy is converted into useful methane exergy, with relatively low exergy destruction and minimal system losses. This behavior indicates favorable thermodynamic performance under mesophilic decentralized operating conditions.

Figure 9b presents the exergy distribution for the modular Sabatier upgrading pathway, which exhibits substantially higher exergy destruction relative to useful methane output. This is mainly attributed to irreversibilities associated with hydrogen production and electrochemical conversion, highlighting the thermodynamic penalty of hydrogen-intensive upgrading pathways.

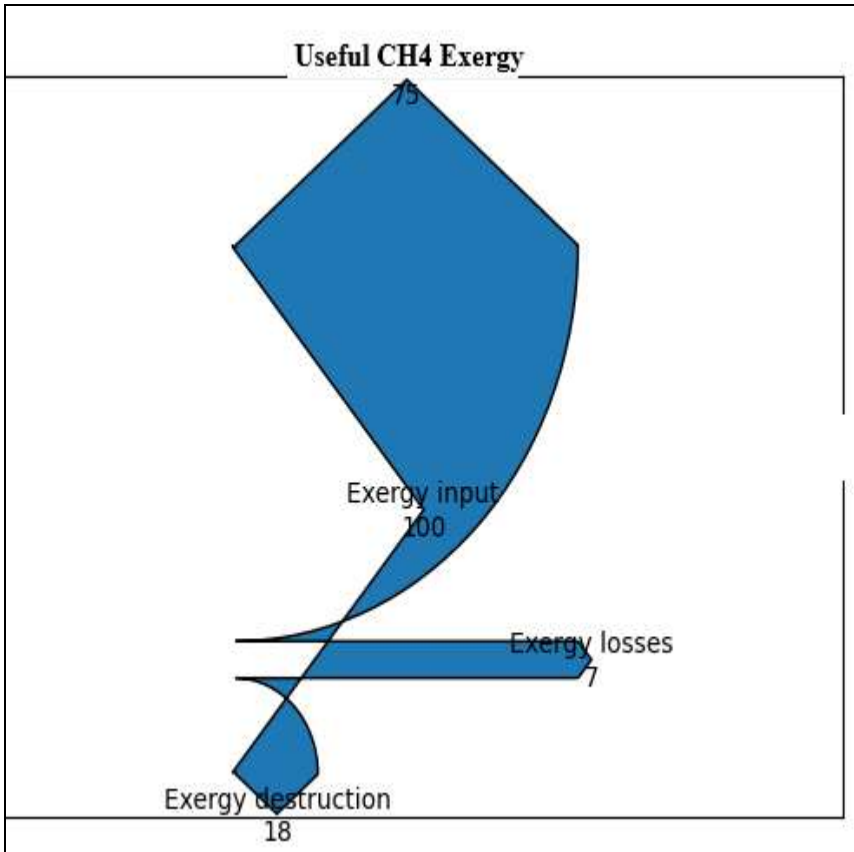


Figure 9 a. Exergy distribution — Water-assisted AD (normalized basis)

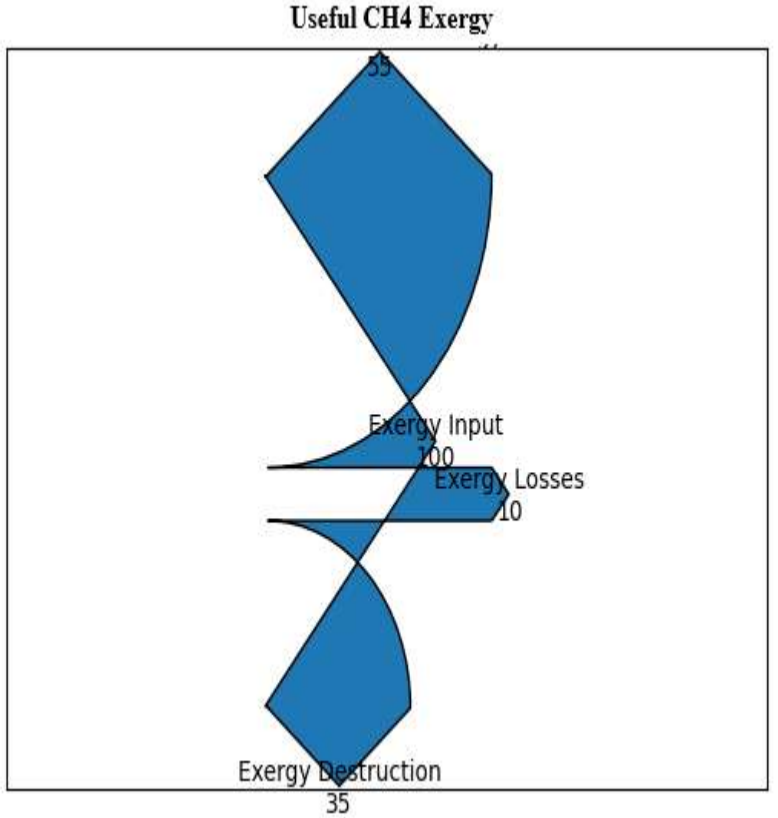


Figure *10* b. Exergy distribution — Modular Sabatier upgrading (normalized basis).

5.4 Environmental Implications

The life-cycle-based evaluation indicates a 42% reduction in CO_2-equivalent emissions compared with scenarios involving uncontrolled methane release. In addition, the complete reuse of digestate further supports circular economy principles by enabling nutrient recycling and reducing the overall environmental burden.

Under resource-constrained conditions, prioritizing biologically optimized methane production provides greater environmental and energy benefits compared with hydrogen-intensive upgrading pathways. Electrochemical integration becomes advantageous primarily in situations where surplus renewable electricity is available, allowing excess electrical energy to be effectively converted into synthetic methane.

6 Conclusions

This study presented a unified heat transfer, energy, and exergy assessment of a water-assisted anaerobic digestion system integrated with modular Sabatier methanation for renewable methane production under decentralized operating conditions.

The results indicate that mesophilic anaerobic digestion operated at 35 °C with a hydraulic retention time of 20 days achieved stable methane concentrations of 60–65%. The incorporation of water-assisted enhancement increased methane yield by approximately 30.5% compared with conventional digestion. Energy analysis further confirmed that the biological pathway maintained a positive net energy output due to its relatively low auxiliary energy requirements for thermal regulation and mixing.

Although the Sabatier upgrading pathway exhibited higher theoretical methane conversion efficiencies (approximately 70–80%), its overall performance was significantly constrained by the high energy and exergy demand associated with hydrogen production. Exergy analysis demonstrated that thermodynamic irreversibilities were dominated by upstream electrolysis processes rather than catalytic methanation alone, resulting in lower overall thermodynamic efficiency for hydrogen-intensive configurations.

The comparative assessment indicates that biologically optimized methane production provides a more energy-efficient and economically viable solution for decentralized renewable energy systems, particularly in resource-constrained environments. Electrochemical upgrading remains a complementary pathway that becomes advantageous mainly under conditions of surplus renewable electricity availability.

Overall, the integrated analytical framework developed in this study enables systematic identification of thermodynamically favorable renewable methane production configurations and supports informed decision-making for sustainable waste-to-energy systems.

Declarations

Funding

This research received no external funding.

Conflict of Interest

The author declares that there are no conflicts of interest regarding the publication of this study.

Data Availability

The data supporting the findings of this study are available within the article. Additional data can be provided by the corresponding author upon reasonable request.

Author Contributions

Ekram Hadi Alaskaree: Conceptualization, Methodology, Formal analysis, Writing – original draft preparation, Writing – review and editing.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

The author consents to the publication of this manuscript.

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