Washington State Conservation Commission

Pilot Testing an Intensified Versatile Anaerobic Digestion (IVAD) System for Dairy Application

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Executive Summary

Dairy farms generate large volumes of manure, which can potentially lead to greenhouse gas emissions, odor, and nutrient runoff if not appropriately managed. Anaerobic digestion (AD) is a proven technology for converting manure into biogas, a renewable energy source, and digestate, a nutrient-rich fertilizer. However, traditional AD systems often require large reactor volumes, long retention times, and significant capital investment, limiting their adoption, especially on small and medium-sized farms.

This project focused on the development, installation, and evaluation of an Intensified Versatile Anaerobic Digestion (IVAD) system designed to overcome these challenges. The pilot scale system, installed at Edaleen Dairy Farm in Lynden, WA, integrates solid-liquid separation, high temperature acidification, and methanogenesis in a compact, two-stage AD configuration.

Key outcomes of the project include:

- *Successful pilot system operation demonstrating stable performance under varied solids loading and feed conditions, with effective material flow control and reliable biogas production.*
- *Enhanced volatile fatty acid (VFAs) production in the acidification reactor under increased solids loading, supporting higher biogas yields.*
- *Development of predictive model linking operational parameters to biogas production, providing a foundation for future process optimization and scale-up.*
- *Implementation of in situ biogas upgrading strategies using hydrogen injection, with potential to achieve high methane concentrations while simplifying the upgrading process.*
- *Techno-economic analysis showing that the IVAD system can achieve substantial cost and energy efficiency benefits compared to conventional technologies, with LCOE reduced by 45% and EROI improved by 87% compared to baseline systems.*

The findings from this project confirm the IVAD system's potential as a scalable, cost-effective solution for sustainable manure management and renewable energy production. However, this technology requires further evaluation at a commercial scale to validate these findings for the final recommendation to the industry. Ongoing work will focus on system optimization, advanced control integration, and demonstration at commercial scale.

Introduction

Anaerobic digestion (AD) is a proven technology for reducing greenhouse gas (GHG) emissions and enhancing the sustainability of dairy operations by converting organic wastes, primarily manure, into biogas and nutrient-rich digestate. Biogas serves as a renewable energy source, reducing reliance on fossil fuels, while the digestate can be used as a substitute for commercial fertilizers. Despite these environmental and economic benefits, widespread adoption of AD systems on dairy farms has been limited. This is mainly due to high installation and operational costs, long hydraulic retention times (HRT), low methane yields, and challenges such as ammonia inhibition and poor solids digestibility.

Conventional AD systems typically require large reactor volumes and extended digestion times to achieve modest biogas yields, particularly when treating dairy manure, which is a difficult substrate due to its high solids and ammonia content. These limitations drive up capital and maintenance costs, making such systems less feasible for small and medium-sized farms. Additionally, conventional designs do not effectively address ammonia toxicity, which can suppress microbial activity and reduce system performance.

To address these challenges, Washington State University (WSU), with funding from the U.S. Department of Energy (DOE), developed the Intensified Versatile Anaerobic Digestion (IVAD) system. This novel two stage system integrates a high temperature anaerobic acidification reactor (AAR) and a thermophilic anaerobic methanogenesis reactor (AMR). The AAR rapidly converts organic matter into volatile fatty acids (VFAs) at hyper-thermophilic temperatures (>70°C), while the AMR converts these VFAs into methane under thermophilic conditions (≥50°C). By decoupling the acidogenesis and methanogenesis processes and recycling undigested solids through a hydrothermal treatment loop, the IVAD system is designed to enhance conversion efficiency, reduce HRT, improve methane yield and purity, and strip ammonia during processing to mitigate inhibition.

The IVAD system was initially validated at bench scale and subsequently scaled up to a pilot system installed at Edaleen Dairy in Lynden, WA. While the DOE-funded effort supported system development and initial commissioning, the limited evaluation period provided insufficient time for a comprehensive performance assessment. To address this, a new project funded by the Washington State Conservation Commission (SCC) was undertaken to conduct an extended pilot-scale evaluation of the IVAD system under real-world conditions and to generate data necessary to support future commercialization.

This report summarizes the outcomes of the SCC-funded pilot scale testing and analysis. The project was structured around four primary objectives:

1. *System Performance Evaluation and Modeling: Operating the pilot system under varied conditions to assess key performance metrics and develop predictive models using kinetic and machine learning approaches.*
2. *In Situ Biogas Upgrading: Introducing hydrogen into the AMR to enhance methane purity through hydrogenotrophic methanogenesis.*
3. *Techno-Economic Analysis (TEA): Comparing the cost effectiveness of the IVAD system to existing commercial technologies.*
4. *Outreach and Education: Engaging stakeholders through fact sheets, site visits, and workshops to promote awareness and facilitate adoption.*

By addressing key technical and economic barriers, the IVAD project aims to provide a scalable, cost effective, and high-performance AD solution for dairy farms in Washington and beyond.

Methods

Pilot-System Configuration and Operation

Pilot-system installation

The main goal of the project was to design, build, and install a pilot-scale anaerobic digestion system on a real dairy farm, to test the system using actual manure resources. The system was installed at Edaleen Dairy Farm in Lynden, WA (Figure 1).

Figure 1. Overview of the pilot-scale Intensified Versatile Anaerobic Digestion (IVAD) system installed in Edaleen Dairy Farm in Lynden, WA

The system includes a centrifuge, an anaerobic acidification reactor (AAR), two anaerobic methanogenesis reactors (AMRs), buffer tanks, pumps, and a control panel. The design allows for the separation of manure solids and liquids, where solids are processed in the AAR to produce volatile fatty acids (VFAs), and liquids are processed in the AMRs to produce methane.

Pilot-system operation

System operation was managed through the control panel, which regulated flow rates, retention times, and monitored operating parameters. Biogas output was continuously monitored to track performance and ensure the system meets productivity targets. The pilot-scale system began regular operation following successful commissioning, marking a significant milestone for the project. The system processes liquid dairy manure continuously, using key components from a two-phase anaerobic digestion system with a centrifuge (Figure 2).

Figure 2. The pilot-scale Intensified Versatile Anaerobic Digestion (IVAD) system

A daily process flow was established to manage material processing efficiently. The centrifuge separates the incoming dairy manure into solids and liquids. The solids are directed to the AAR, where they are converted into volatile fatty acids (VFAs). The liquids, along with VFAs from the AAR and centrifuged liquid, are fed into the AMRs for further conversion into biogas. Recycled flows between the AAR and AMRs help maintain balance and stability within the system.

Regular sampling and monitoring of influent and effluent streams began in September 2024. Initial results indicated stable system performance, with increasing VFA concentrations and biogas production in the AAR, and expected start-up dynamics in the AMRs, including variable sCOD removal and steady biogas output.

Evaluating AAR Performance Under Varied Solids Loading Conditions

Following the establishment of a consistent daily process, system testing focused on evaluating the AAR's response to increasing solids loadings. Dairy fibers, sourced from flushed manure and processed to increase solids content and reduce particle size, were used as the primary solids input. These prepared fibers supported the evaluation of the AAR's ability to handle higher solids levels and enhance volatile fatty acids (VFAs) production (Figure 3).

Figure 3. Size reduction process by grinder and the ground solids

The prepared fibers were introduced into the AAR in sequencing batch mode across three controlled periods:

- ***Period 1:*** *Approximately 20 kg of ground solids were mixed with AMR effluent in the mixing station and gradually fed into the AAR to minimize clogging risk. After feeding, the AAR operated in batch mode for 10 days. Samples were collected during and after the batch to assess VFA concentration changes. Effluent was transferred to the AMR for further digestion.*
- ***Period 2:*** *As a next sequencing cycle, a similar quantity of solids was combined with AMR effluent, fed into the AAR, and followed by a 10-day batch operation. Samples were collected for analysis at the end of the batch phase.*
- ***Period 3:*** *Solids and AMR effluent were again mixed and fed into the AAR, followed by a 10-day batch operation. Sampling was conducted during feeding and at the conclusion of the batch to monitor reactor performance.*

Developing predictive model of the system

In parallel with system modifications, significant progress was made toward the development of a comprehensive dataset to support kinetic and machine learning-based modeling of the IVAD system. The initial phase focused on integrating and organizing historical data collected from bench-scale experiments (Figure 4).

Figure 4. Data integration for kinetic and machine learning

Analyzed data, such as VFA concentration profiles from both the AAR and UASB/AMR, were sorted by sampling date and aligned with corresponding operational records, including inlet conditions, flow rates, and gas production measurements. The dataset was categorized into three primary groups to support model development along with Operational Parameters (ex., temperature, and hydraulic retention time (HRT)), Measurement Parameters (ex., pH, VFA composition, and TS/VS), and Output parameter (ex., Produced Biogas volume). To ensure completeness and model-readiness, imputation techniques were applied to address missing data points and improve continuity.

Implementing a new component for in situ biogas upgrading to produce purer natural gas

The anaerobic digestion system was operated similarly to a pilot plant setup. The anaerobic methanogenic reactor (AMR) at the BBEL laboratory in Pullman were modified with the addition of a liquid level sensor and a pressure sensor, both integrated into the control system to enable accurate monitoring and control of reactor parameters (Figure 5). The anaerobic acidification reactor was utilized to generate volatile fatty acids (VFAs), which are key intermediates in anaerobic digestion and serve as substrates for methanogenic archaea. This hyperthermophilic anaerobic acidification reactor (AAR) was inoculated with dairy manure and primary sludge sourced from the anaerobic digester at the Pullman Wastewater Treatment Plant.

Figure 5. Modified AMR reactor for testing hydrogen injection

The methanogenic stage employed an up flow anaerobic sludge blanket (UASB) reactor, operated at thermophilic conditions (52-54 °C). Although UASB reactors have shown promise in treating dairy wastewater at pilot and lab scales, their commercial-scale application remains relatively *limited due to operational and design challenges. However, our system uniquely enabled its use for this purpose, offering a reduction in hydraulic retention time. The microbial granules in a UASB reactor allow the system to sustain different conditions such as pH changes, temperature fluctuations, and substrate fluctuations.*

The reactor was tested under varying organic loading conditions by adjusting the feed. As the concentration of dissolved nutrients increased, biogas production also improved. The produced biogas contained approximately 70% methane regardless of organic loading, with the remainder primarily consisting of CO_2.

To enhance biogas quality, hydrogen (H_2) gas was injected into the system to biologically convert CO_2 into methane, following the CO_2:H_2 ratio of 1:4The theoretical outcome of this conversion is one molecule of methane and two molecules of water per molecule of CO_2.

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

Conducting techno-economic analysis to compare the economics of the system with the existing technologies

A techno-economic analysis was carried out to compare the IVAD system with a typical digestion system (called the baseline system). The analysis focused on two main performance measures:

- *Levelized Cost of Energy (LCOE): the cost to produce energy over the system's lifetime*
- *Energy Return on Investment (EROI): how much energy is produced for every unit of energy used*

$$LCOE = \frac{\text{Total Life Cycle Cost}}{\sum_{t=1}^{N} \frac{\text{System Energy Output}}{(1+\text{i})^t}} = \frac{\sum_{t=1}^{N} \frac{\text{After Tax Cash Flow}}{(1+\text{i})^t}}{\sum_{t=1}^{N} \frac{\text{System Energy Output}}{(1+\text{i})^t}} = \frac{\$}{\text{kWh or MMBtu}}$$

$$EROI = \frac{\text{Energy Output}}{\text{Energy Intput}} = \frac{Q}{S_1 + S_2}$$

Where:
Q = rate of energy output (kWh/analysis period) for the entire energy production system
S_1 = the conversion energy input into the process (kWh/analysis period)
S_2 = is the embodied energy in the various items the energy production system uses (kWh/analysis period)
i = the discount rate
t = the year
N = the system lifetime in years

Calculations followed industry-standard equations and used data from Regenis LLC, the National Renewable Energy Laboratory (NREL), and computer simulations in Aspen Plus. The systems were compared over a 30-year lifetime.

The baseline system modeled a patented double-U-shaped mixed plug flow digester operating at 37°C, with 22 days hydraulic retention time (HRT) and a working volume of 11,249 m³. Manure *was processed through solid separation and flocculation equipment, producing biogas upgraded for renewable natural gas (RNG) via water scrubbing.*

The IVAD system model featured smaller reactor volumes and shorter retention times, including:

- *Anaerobic Acidification Reactor (AAR): 1,166 m^3 working volume, 6-day HRT*
- *Hydrothermal Treatment (HTT) Reactor: 4 m^3 working volume, 1-hour HRT*
- *Thermophilic Anaerobic Methanogenic Reactor (TAMR): 171 m^3 working volume, 1-day HRT*
- *Mesophilic Anaerobic Methanogenic Reactor (MAMR): 503 m^3 working volume, 1-day HRT*

Since the smaller reactor sizes in the IVAD system contributed to reduced heat loss and lower equipment costs, the IVAD system required less equipment and energy for gas upgrading. For this analysis, 75% methane content was used in calculations.

Outreach and education activities

As part of the project's outreach and education efforts, the team actively engaged with stakeholders and the broader community to share knowledge about the IVAD system. Do-Gyun Kim was stationed in Lynden to oversee pilot-scale operations and facilitate direct interaction with local partners and visitors (Figure 6).

During the operational period, multiple site visits and tours were conducted to showcase the system's design, installation, and daily operation. These visits helped familiarize stakeholders with the practical aspects of the technology and its potential applications.

Project results and system details were also shared at regional events.

- *A poster presentation was delivered at the Northwest Bioenergy Summit on October 15, 2024*
- *A project description was prepared in collaboration with extension specialists Georgine Yorgey and Kristen Johnson for dissemination at the Washington State Dairy Conference, Annual Meeting & Trade Show, held December 2-4, 2024, in Pasco, WA.*

Additional outreach activities are ongoing, including a planned site visit by the WACC stakeholder team to observe the system during operation.

Figure 6. Site Visits

Results

Evaluating AAR Performance Under Varied Solids Loading Conditions

The performance of the anaerobic acidification reactor (AAR) under different solids loading conditions demonstrated clear trends in volatile fatty acids (VFAs) production and biogas output (Figure 7).

In Period 1, although VFA concentration decreased, biogas production increased from 84 L/day to 132 L/day, with VFA productivity rising from 0.1 g/L/day to 0.25 g/L/day.

In Period 2, reactor performance improved during the feeding phase, as VFA concentration increased from 0.5 g/L to 2.8 g/L, average biogas production reached 220 L/day, and VFA productivity rose to 0.8 g/L/day. During the subsequent batch phase, VFA concentration climbed further to 3.7 g/L, while biogas production averaged 141 L/day.

In Period 3, the reactor achieved its highest VFA concentration at 4.3 g/L and peak VFA productivity of 0.97 g/L/day. Biogas production during this phase averaged 197 L/day, with methane content at 30%.

Overall, the results indicate that VFA production and productivity steadily increased with higher solids loading, while biogas output varied depending on the operational phase. These findings demonstrate the AAR's capacity to handle increasing solids levels while supporting biogas production.

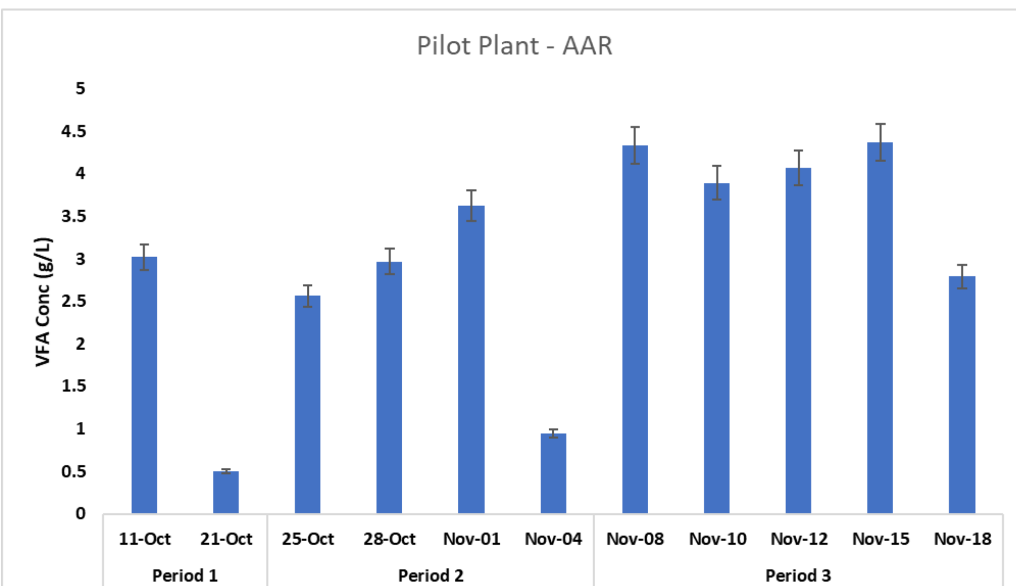

Figure 7. Changes of VFA concentrations in the AAR reactor under different solids loadings

Developing a predictive model of the system

The predictive model revealed clear relationships between operational conditions and system performance. Specifically, the model identified how influent concentration and hydraulic retention time (HRT) influence biogas production rates in the AMR reactor (Figure 8). These trends offer valuable insight into reactor behavior across varying load conditions. While the figure focused on the AMR, the results point to the broader potential of the IVAD system for predictive control and operational optimization at larger scales.

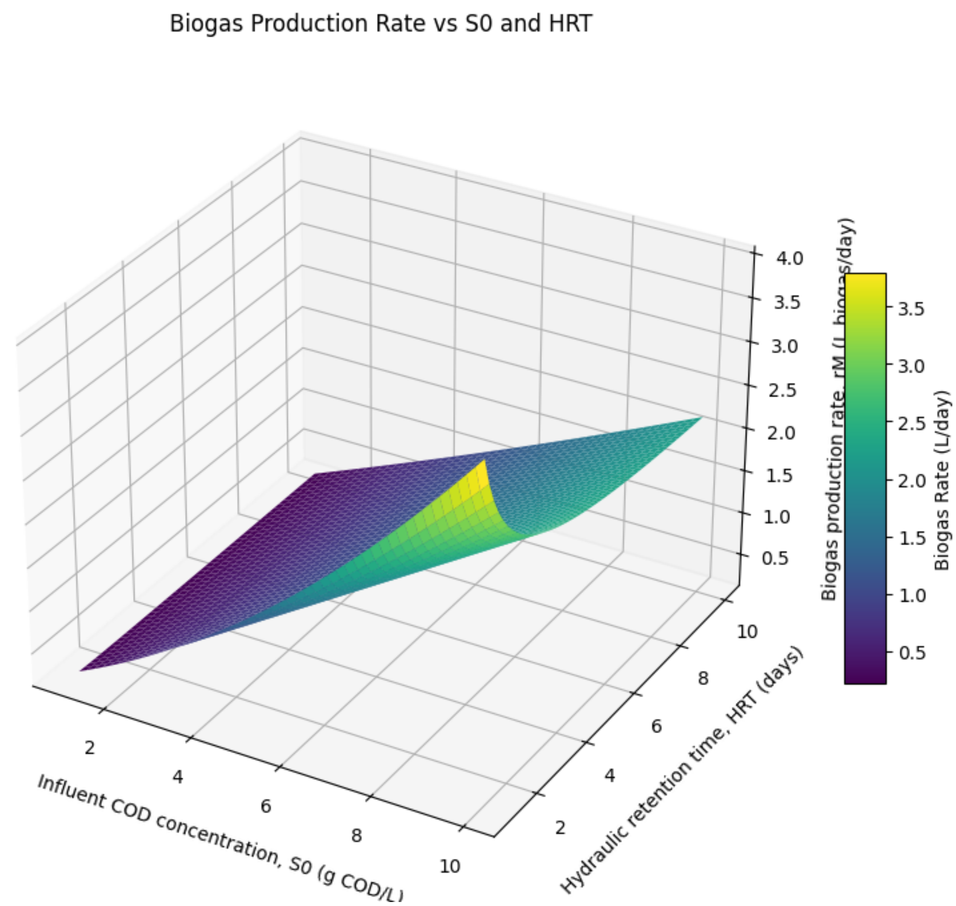

Figure 8. Relationship between influent concentration and biogas production rate

The analysis confirmed the AMR reactor's ability to efficiently degrade organic matter and produce biogas under a range of influent concentrations. The strong positive correlation between influent soluble COD (sCOD) levels and degradation rates demonstrates the reactor's robustness in handling different feed strengths, supporting its suitability for scale-up and high biogas yield applications.

Implementing a new component for in situ biogas upgrading to produce purer natural gas

Over several days of H_2 injection, methane content in the biogas gradually increased, while CO_2 levels decreased (Figure 9). Methane purity peaked at 83.5 %, with stable levels maintained around 79%. The system's pH rose from approximately 7.3 to 7.9 due to reduced dissolved CO_2 in the reactor; however, this did not adversely affect reactor performance, as methanogenic archaea typically prefer a neutral to slightly alkaline pH range (between 6.5 to 8.2).The observed improvement in methane purity demonstrates the system's strong potential for producing high-quality biogas with shorter hydraulic retention time, which means smaller reactors and shorter cycles. Significantly, H_2 injection did not negatively impact overall reactor productivity, which remained consistent at approximately 2–3 L/L/day. Additionally, more than 90% of the VFAs, originally produced in the AAR from the breakdown of organic material, including dairy solids, were converted during H_2 injection.

Figure 9. Biogas composition measured in H2 injection testing (without considering the residual H2 collected)

Microbial community analysis after hydrogen injection revealed an increased presence of hydrogenotrophic methanogens, such as Methanobacterium formicicum and Methanothermobacter wolfeii, which convert CO_2 and H_2 into CH_4, along with acetoclastic methanogens such as Methanosarcina acetivorans, which produce CH_4 from acetic acid.

Conducting techno-economic analysis to compare the economics of the system with the existing technologies

As a result, the IVAD system required a smaller biogas upgrading unit without a compressor, contributing to cost and energy savings. The levelized cost of energy (LCOE) compares the total lifetime cost of the system to the amount of energy it produces. For this analysis, both the baseline system and the IVAD system were assumed to produce the same amount of methane. The calculated LCOE was $18.05 per MMBTU for the baseline system and $19.18 per MMBTU for the IVAD system. Sensitivity analysis (Figure 10) showed that LCOE is most influenced by the *methane production rate, equipment cost, and capital investment. Operating costs and the start-up period had less impact.*

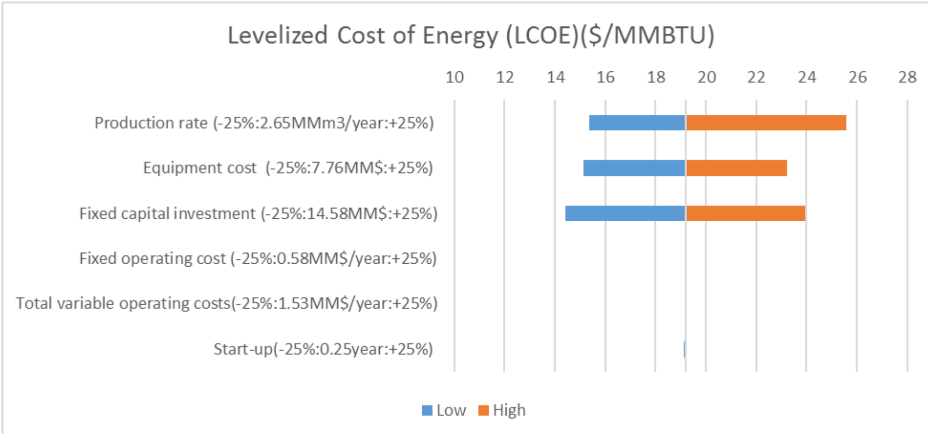

Figure 10. Sensitivity analysis of LCOE for IVAD

The energy return on investment (EROI) measures how much energy is produced compared to the energy required to run the system. Energy inputs include heating, heat loss, and equipment power use—with heating and heat loss being the largest contributors. The EROI was 1.71 for the baseline system and 1.73 for the IVAD system. Sensitivity analysis (Figure 11) revealed that methane production rate, heating demand, and heat loss had the greatest effect on EROI.

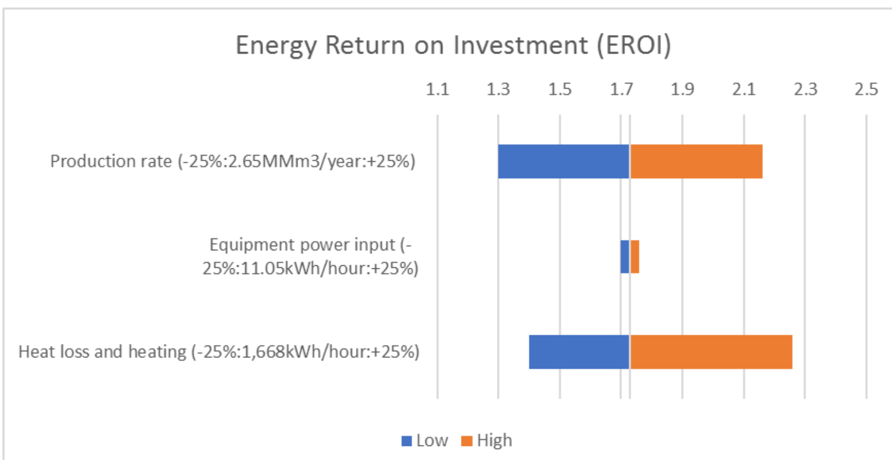

Figure 11 Sensitivity analysis of EROI for IVAD

Through design improvements, the IVAD system reached a methane productivity of 1.18 m³/m³/day, which is 184% higher than the baseline's 0.64 m³/m³/day. This resulted in a reduced LCOE of $10.04 per MMBTU, a 45% cost reduction from the baseline and well above the 25% improvement goal. The EROI improved to 3.19, an 87% increase over the baseline, also exceeding the target.

Discussion & Conclusions

Pilot-System Configuration and Operation

The pilot system was successfully designed, installed, and operated at the dairy farm site, demonstrating its capability to process dairy manure efficiently under real farm conditions. The integrated configuration supported stable daily operation and effective material flow management, while achieving the targeted levels of biogas production.

The pilot operation also highlighted opportunities for further optimization, including fine-tuning retention times, improving solids handling, and enhancing the balance between acidification and methanogenesis stages to maximize biogas yield. The system showed potential to adapt to different manure feedstocks and loading conditions, providing a strong foundation for commercial-scale application. Continued refinement of operational controls and automation will further improve system stability, efficiency, and cost effectiveness.

Evaluating AAR Performance Under Varied Solids Loading Conditions

The evaluation of the anaerobic acidification reactor (AAR) under varying solids loading conditions demonstrated that the system effectively adapted to increased solids input and maintained stable operation. Across the three test periods, VFA production and productivity improved consistently as solids loading increased, indicating that the AAR successfully converted solids into volatile fatty acids under sequencing batch operation.

The highest VFA concentration achieved was 4.3 g/L, with a peak VFA productivity of 0.97 g/L/day, reflecting the system's capacity to handle higher solids loadings without operational failure. Biogas production also responded positively to the increased VFA levels, though output varied during different phases due to changes in operational mode and reactor dynamics.

These results highlight the potential of the AAR to support enhanced biogas production when integrated with downstream methanogenesis reactors. Continued optimization of solids loading, retention times, and operational parameters can further improve system efficiency and support cost-effective, high-performance manure management solutions at a commercial scale.

Developing a predictive model of the system

The positive correlation between influent soluble COD (sCOD) levels and degradation rates confirmed the reactor's ability to handle varying feed concentrations efficiently. This finding supports the AMR's suitability for flexible operation and scale-up, contributing to higher biogas yields and improved system performance at larger scales.

These results lay the groundwork for further refinement of kinetic and machine learning models to support real-time operational adjustments, enhance process stability, and maximize biogas production in commercial anaerobic digestion systems.

Implementing a new component for in situ biogas upgrading to produce purer natural gas

The integration of in situ biogas upgrading using hydrogen injection offers a promising pathway for enhancing methane content directly within the reactor while simplifying the upgrading process. This approach not only improves biogas quality for grid injection or vehicle fuel use but also presents an opportunity to store excess renewable energy, such as that generated from solar or wind, by converting it into methane via hydrogen addition.

Compared to conventional biogas upgrading systems, which are often costly and complex, the in-situ method provides a cost-effective alternative capable of producing biogas with methane concentrations above 95%, as demonstrated in prior studies.

Our initial findings confirm the potential of hydrogen injection within the two-stage IVAD system. However, further work is required to increase dissolved hydrogen availability, enhance microbial hydrogen consumption rates, and integrate automated controls and water electrolysis units. These improvements will be critical for optimizing system performance and making this technology viable for broader adoption in commercial applications.

Conducting techno-economic analysis to compare the economics of the system with the existing technologies

The techno-economic analysis identified three key strategies for improving both the levelized cost of energy (LCOE) and the energy return on investment (EROI) of the IVAD system. These strategies are: Increasing methane production to generate more energy and reduce cost per unit of output; Eliminating the need for external biogas upgrading by achieving in situ carbon dioxide removal directly within the AMR reactor; and reducing hydraulic retention times (HRT) to lower reactor volumes, which would decrease equipment costs and reduce heat loss.

Specific opportunities include reducing the HRT of the hydrothermal treatment (HTT) reactor from 1 hour to 0.5 hours, as smaller agitated reactors are cost-effective and improve mass transfer. The AAR's HRT could be shortened by decoupling solid retention time (SRT) from HRT, and further reductions in HRT for the TAMR could enhance system efficiency.

The IVAD system currently achieves a methane productivity of 1.18 m^3/m^3/day, or 184% of the baseline system's performance. This results in an LCOE of $10.04 per MMBTU, a 45% reduction from the baseline, and an EROI of 3.19, representing an 87% improvement.

Acknowledgements

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