

Integrated Process Development and Optimization of Anaerobic Digestion of Septic Sludge for Renewable Biomethane Generation

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INTRODUCTION & AIM

The growing global demand for sustainable energy and effective waste management has intensified the search for renewable alternatives to fossil fuels. Among various organic waste streams, septic tank sludge—a byproduct of domestic wastewater treatment—represents an abundant yet underutilized resource. Rich in biodegradable organic matter, this sludge poses significant environmental and public health challenges if not properly managed. However, its high organic and nutrient content presents a valuable opportunity for renewable energy recovery through anaerobic digestion (AD), a biological process that converts organic substrates into biogas primarily composed of methane (CH₄) and carbon dioxide (CO₂).

Anaerobic digestion offers multiple benefits, including waste volume reduction, pathogen control, nutrient recovery, and the production of biomethane, which can be upgraded and utilized as a sustainable fuel for electricity, heating, or transportation. Despite its advantages, the efficiency of AD is strongly influenced by operational parameters such as temperature, retention time, organic loading rate, and feedstock composition. Septic sludge, with its variable characteristics and high solids content, often exhibits process instability and lower gas yield compared to other organic substrates. Therefore, process optimization and integrated system design are crucial to enhance biomethane yield, process stability, and overall energy recovery efficiency.

This study aims to develop and optimize an integrated process for efficient energy recovery from septic sludge. Using Aspen Plus simulation and Response Surface Methodology (RSM), key parameters such as temperature, retention time, and organic loading rate were optimized to maximize methane yield and energy efficiency. The approach supports sustainable waste management, resource recovery, and the advancement of circular bioeconomy and net-zero energy goals.

METHOD

This section provides detailed procedures for the characterisation of the septic tank sludge and anaerobic digestion. The septic tank sludge was collected from local residence around Yelwan Bauchi and conduct characterisation such as proximate and ultimate analysis on the septic tank sludge. Aspen Plus version 14.0 was used to design a process for the anaerobic digestion of the septic tank sludge using experimental data from literature, also carry out optimization of the operating conditions using Design Expert version 13. Figure 1 shows the methodological flow diagram used to achieve the research objectives

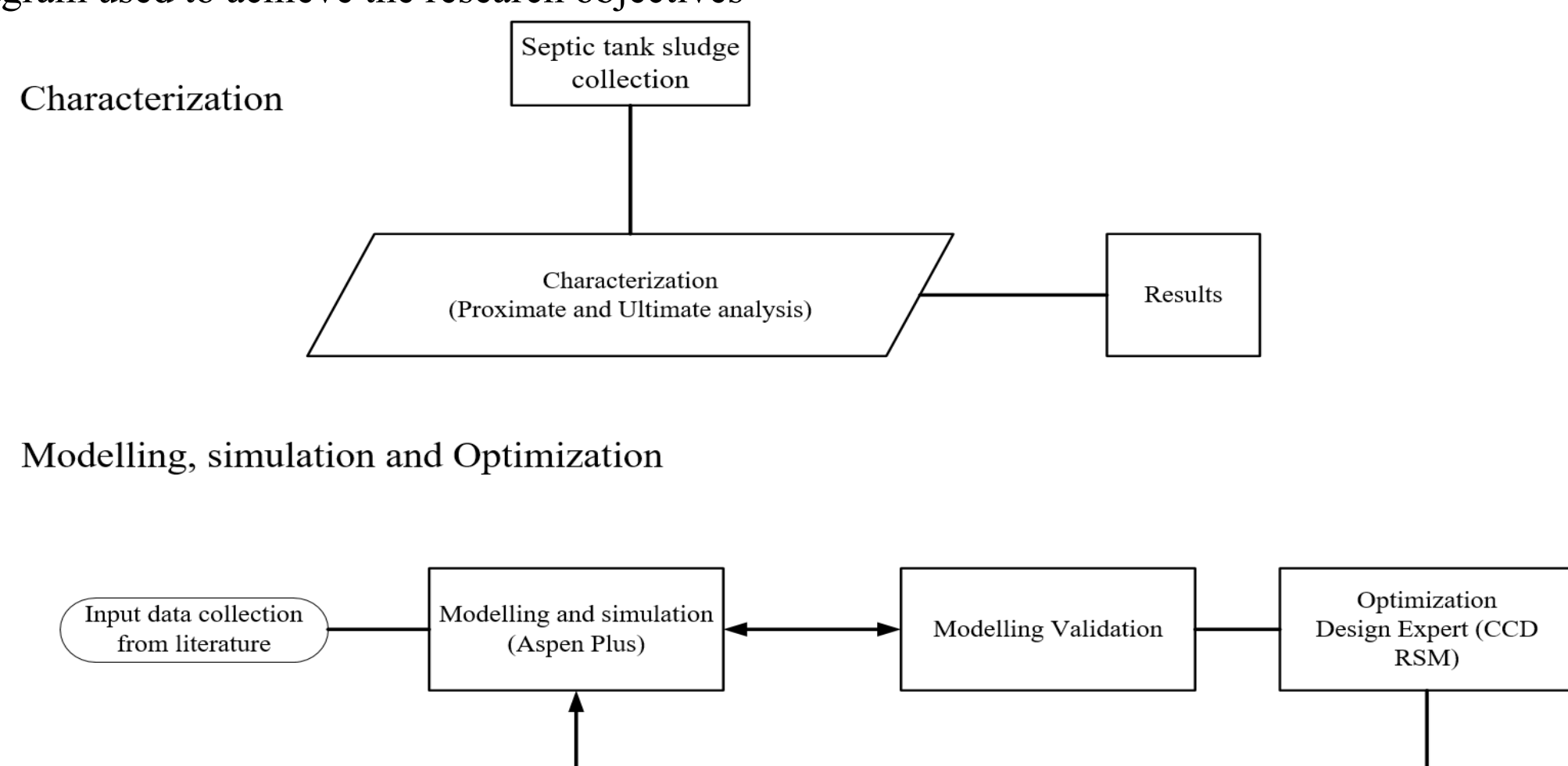


Figure 1: Flow Chart for Characterisation of Septic Tank Sludge and Anaerobic Digestion Process for Biomethane Production and Optimization

1. Physicochemical Characterization of Feedstock

Septic tank sludge was collected and analysed for physicochemical properties through proximate and ultimate analyses following ASTM standards. The high heating value (HHV) was determined using a bomb calorimeter, providing essential input parameters for process modelling and energy balance evaluation in anaerobic digestion studies.

2. Process Design and Simulation

An anaerobic digestion system was designed and modelled in Aspen Plus to simulate the conversion of septic sludge into biomethane. The process configuration included four key stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Appropriate thermodynamic and kinetic models were selected to represent biochemical reactions, and input data from the characterization study were integrated into the simulation. The model incorporated material and energy balances to predict methane yield, biogas composition, and process efficiency under varying operating conditions.

13. Model Validation

The developed Aspen Plus model was validated using experimental or literature data on methane yield and degradation efficiency for similar sludge compositions. Statistical validation was carried out by comparing simulated and observed results using regression analysis, with the coefficient of determination (R²) employed to evaluate model accuracy. A strong correlation between simulated and experimental data confirmed the reliability of the developed model.

4. Process Optimization

To determine the optimal operating conditions for maximum biomethane yield, Response Surface Methodology (RSM) with a Central Composite Design (CCD) was applied. The key process variables, temperature (25–35°C), hydraulic retention time (HRT, 5–35 days), and organic loading rate (OLR, 15–35 L day^{−1}) were systematically varied within defined ranges. The experimental design generated predictive models to quantify the interaction effects of these parameters on methane yield and volatile solids degradation. Statistical analysis of variance (ANOVA) was performed to assess model significance, and optimal conditions were identified by maximizing the response function.

5. Performance Evaluation

The optimized model was used to evaluate overall system performance in terms of biomethane yield, energy conversion efficiency, and carbon reduction potential. The results were compared with baseline values to quantify the improvements achieved through parameter optimization. The validated and optimized model serves as a decision-support tool for scaling up septic sludge-to-energy systems under circular bioeconomy frameworks.

RESULTS & DISCUSSION

Physicochemical Characterization, Modelling, and Optimization of Septic Tank Sludge

Septic tank sludge was analysed to assess its potential as anaerobic digestion (AD) feedstock. Ultimate analysis showed a high heating value of 14.324 MJ/kg, with elemental composition of 33.80% C, 5.86% H, 24.81% N, 0.0136% S, and 35.51% O. Proximate analysis indicated 44.55% volatile matter, 34.86% fixed carbon, 47.55% moisture, and 20.59% ash, confirming sufficient organic content for biogas production, consistent with municipal sludge studies (David et al., 2023). AD stability was monitored via pH (6.34–7.42), volatile fatty acids (<0.90 g/L), and total ammonia nitrogen (0.65–0.75 g/L), showing no inhibition.

The AD process was simulated in Aspen Plus, including hydrolysis, digestion, and biogas separation. Validation against literature data (Shen et al., 2024; de la Cruz-Azuara et al., 2024; Nauman et al., 2024) showed minimal deviation (0.04–0.15%), confirming model accuracy.

Process optimization using Response Surface Methodology with a Central Composite Design assessed hydrolysis temperature, digester temperature, hydraulic retention time (HRT), and organic loading rate (OLR). ANOVA identified digester temperature, HRT, and OLR as highly significant ($p < 0.05$), while hydrolysis temperature was less influential ($p = 0.096$). The regression model achieved $R^2 = 0.9917$. Optimal biomethane yield (99.98% Vol.) occurred at 35 °C hydrolysis, 60 °C digester temperature, 35-day HRT, and 37.91 L/day OLR, highlighting the critical role of temperature, retention time, and loading rate in maximizing gas production.

This integrated experimental and modelling study demonstrates that precise operational control enhances methane generation from septic sludge. The validated model provides a reliable framework for process scale-up, supporting sustainable waste-to-energy conversion and advancing circular bioeconomy goals.

CONCLUSION

Septic tank sludge exhibits favourable physicochemical properties, including high organic content and stable pH, VFA, and TAN levels, making it suitable for anaerobic digestion. Aspen Plus modelling accurately simulated the AD process, and optimization using Response Surface Methodology identified digester temperature, hydraulic retention time, and organic loading rate as key factors for maximizing biomethane yield. Under optimized conditions, methane production reached 99.98% Vol., demonstrating the potential of precise operational control to enhance gas output. This integrated experimental and modelling approach provides a reliable tool for process scale-up, supporting efficient waste-to-energy conversion and contributing to sustainable circular bioeconomy initiatives.

FUTURE WORK / REFERENCES

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