



Optimizing Biogas Production through Co-Digestion of Algal Biomass and Food Waste in a Mesophilic Batch Anaerobic Reactor

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Abstract

Interest in algal biomass as a renewable feedstock for liquid and gaseous biofuels has increased because algae can exhibit higher photosynthetic productivity and energy potential than many terrestrial biomass resources and portions of municipal solid waste streams. This study investigated the optimization of biogas generation by anaerobic digestion of marine algal biomass and food waste, both separately and in combination, using a mesophilic batch bioreactor. Algal samples were collected from coastal waters in Nigeria, while food waste was obtained from restaurants at Igbinedion University. Reactor operating conditions were monitored throughout the digestion period to maintain stable mesophilic performance. The reactor temperature was maintained at $37 \pm 1^\circ\text{C}$. Average daily biogas yields were approximately $0.21 \text{ m}^3 \text{ day}^{-1}$ for food waste alone (FW), $0.14 \text{ m}^3 \text{ day}^{-1}$ for algal biomass alone (AB), and $0.26 \text{ m}^3 \text{ day}^{-1}$ for the co-digestion mixture of food waste and algal biomass (FWAB). The higher gas yield achieved during co-digestion indicates a synergistic effect between the two substrates, likely associated with improved nutrient balance, buffering capacity, and substrate biodegradability. The findings demonstrate that combining algal biomass with food waste can enhance biogas productivity under mesophilic batch digestion and supports the use of algae-containing organic waste streams as promising feedstocks for decentralized renewable energy production.

Keywords: Algal biomass; food waste; anaerobic digestion; co-digestion; biogas optimization; mesophilic batch reactor. Important note on the "25-page chapter paper" request

1. INTRODUCTION

The transition away from fossil fuels has intensified interest in renewable energy technologies that simultaneously recover energy and manage organic wastes. Anaerobic digestion (AD) is one such technology because it converts biodegradable organic matter into biogas—a mixture dominated by methane (CH_4) and carbon dioxide (CO_2)—while also producing a nutrient-rich digestate. Food waste (FW) is widely recognized as a highly biodegradable substrate for AD; however, rapid acidification and imbalance between carbon and nutrients can impair reactor stability when food waste is digested alone. Algal biomass (AB), particularly marine algae, offers an attractive complementary feedstock because it contains carbohydrates, proteins, minerals, and trace elements that may improve nutrient balance and buffering capacity during digestion.

Researchers have increasingly examined algae as a bioenergy feedstock owing to their high areal productivity, rapid growth, and ability to utilize wastewater nutrients and non-arable land. Compared with many terrestrial energy crops, algae can potentially achieve higher biomass yields without directly competing for fertile agricultural land. Nevertheless, mono-digestion of algal biomass often faces challenges related to recalcitrant cell walls, seasonal compositional variability, and suboptimal carbon-to-nitrogen (C/N) ratios. Co-digestion with food waste has therefore emerged as a promising strategy to exploit synergistic interactions between substrates.

The present study evaluates biogas optimization through mesophilic batch anaerobic digestion of marine algal biomass, food waste, and their combination. The specific objectives are to:



1. Compare biogas yields from food waste alone, algal biomass alone, and a food waste–algal biomass co-digestion mixture.
2. Monitor reactor temperature and operational stability under mesophilic conditions.
3. Interpret the observed performance differences in terms of substrate synergy, nutrient balance, and biodegradability.

4. Discuss implications for decentralized waste-to-energy systems in coastal and university settings.

Research focus

This chapter focuses on biogas optimization by co-digestion, not on life-cycle assessment or algal cultivation engineering. The core question is whether combining marine algal biomass with food waste under stable mesophilic batch conditions improves biogas yield relative to digesting either substrate alone.

2. LITERATURE REVIEW

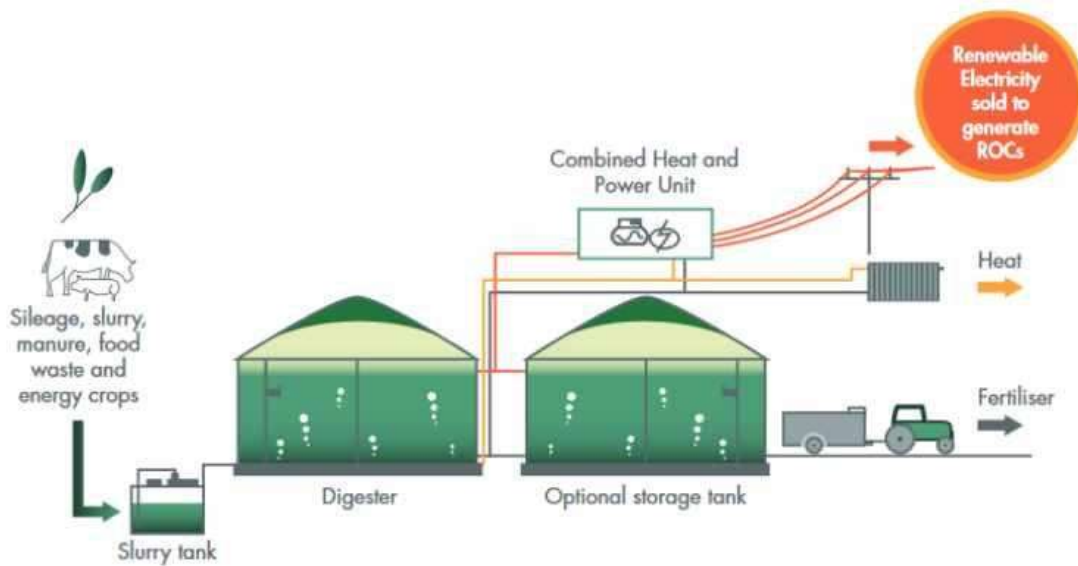


Figure 1. Simplified anaerobic digestion plant schematic. Source: NIAO report (2020)¹

Figure 2.1: Global Renewable Energy Sources and Their Contribution to Sustainable Development

Figure 2.1 presents the major renewable energy sources currently utilized worldwide, including solar, wind, hydropower, biomass, geothermal, and ocean energy. The figure highlights the increasing importance of biomass-based energy systems in addressing global energy demand and environmental sustainability concerns. Biomass energy is particularly significant

because it provides a means of converting organic waste materials into useful energy while simultaneously reducing environmental pollution. The figure establishes the relevance of biogas technology within the broader renewable energy sector and demonstrates why researchers are increasingly focusing on alternative feedstocks such as algae and food waste.



Figure 2.2: Classification of Biomass Resources for Bioenergy Production

Figure 2.2 illustrates the various categories of biomass resources used for renewable energy generation. These include agricultural residues, forestry wastes, animal manure, municipal solid waste, food waste, and algal biomass. The figure emphasizes that food waste and algae are among the most promising

feedstocks because of their high organic content and rapid biodegradability. It also demonstrates the diversity of biomass resources available for anaerobic digestion and highlights the potential of waste-to-energy technologies in promoting sustainable resource utilization.



Figure 2.3: Sources and Types of Food Waste Generated in Institutions

Figure 2.3 shows the major sources of food waste within institutional environments such as universities, restaurants, hotels, hospitals, and residential facilities. Food waste typically consists of leftover food, fruit peels, vegetable residues, cooked food remnants, and expired food products. The figure illustrates the increasing volume of food waste generated globally and emphasizes the environmental challenges associated with improper

disposal. The recovery of energy through anaerobic digestion offers a sustainable solution for managing these waste streams.

2.1 Anaerobic Digestion Fundamentals

Anaerobic digestion proceeds through four interacting microbial stages: hydrolysis, acidogenesis, acetogenesis,



and methanogenesis. Hydrolytic bacteria first convert complex polymers into soluble monomers. Acidogenic organisms then produce volatile fatty acids (VFAs), alcohols, hydrogen, and CO₂. Acetogens convert intermediate products to acetate, hydrogen, and CO₂, which are subsequently transformed into methane by methanogenic archaea. Because methanogens are sensitive to pH, temperature fluctuations, and toxic compounds, stable operation generally requires balanced substrate feeding and adequate buffering.

Mesophilic digestion (typically 35–38°C) is widely used because it offers relatively stable microbial communities, moderate energy requirements, and robust methane production. Temperature control within a narrow range is important because microbial activity and gas production can decline when reactors experience sustained deviations from the target operating window.

2.2 Food Waste as a Biogas Feedstock

Food waste contains readily biodegradable carbohydrates, fats, and proteins, making it one of the highest-yielding organic substrates for AD on a volatile solids basis. However, its rapid hydrolysis can cause accumulation of VFAs, lowering pH and inhibiting methanogens if buffering capacity is insufficient. Studies frequently report improved stability when food waste is co-digested with substrates that provide alkalinity, structural carbon, or complementary nutrients.

2.3 Algal Biomass for Bioenergy

Algae have attracted attention because they can be cultivated in saline, brackish, or wastewater systems and may exhibit high productivity. Their biochemical composition varies widely among species and seasons, with carbohydrates, proteins, lipids, ash, and minerals differing substantially across environments. For anaerobic digestion, algal proteins and minerals can provide nutrients and trace elements, but excessive nitrogen may lead to ammonia inhibition in some cases. In addition, some macroalgae and microalgae possess cell wall structures that limit hydrolysis unless pretreated.

2.4 Co-Digestion Synergy

Co-digestion combines two or more substrates to improve reactor performance relative to mono-digestion. The main mechanisms proposed in the literature include:

1. Nutrient balancing: mixing carbon-rich and nitrogen-rich wastes to approach a more favorable C/N ratio.
2. Buffering enhancement: minerals and alkalinity from one substrate can moderate pH swings generated by another.
3. Dilution of inhibitors: problematic compounds present in one feedstock may be diluted below inhibitory thresholds.
4. Improved microbial diversity: mixed substrates may support a broader microbial consortium capable of more complete degradation.

For algae–food waste systems, the literature generally suggests that moderate inclusion of algal biomass can improve process stability and gas yield, although the optimal mixing ratio depends on algal composition, pretreatment, solids concentration, and reactor configuration.

2.5 Research Gap

Many studies have examined food waste digestion or algal digestion separately, while fewer have evaluated co-digestion under simple batch conditions using locally sourced marine algae and institutional food waste. Practical data from tropical coastal contexts remain limited. This study contributes evidence on relative biogas performance under controlled mesophilic batch operation using substrates collected in Nigeria.

3. MATERIALS AND METHODS

3.1 Study Context and Feedstock Sources

Marine algal biomass was collected from coastal waters in Nigeria. Food waste was obtained from restaurants within Igbinedion University. The food waste stream primarily comprised cooked rice residues, vegetable scraps, soup remnants, and other biodegradable kitchen wastes. Non-biodegradable contaminants were manually removed before processing.



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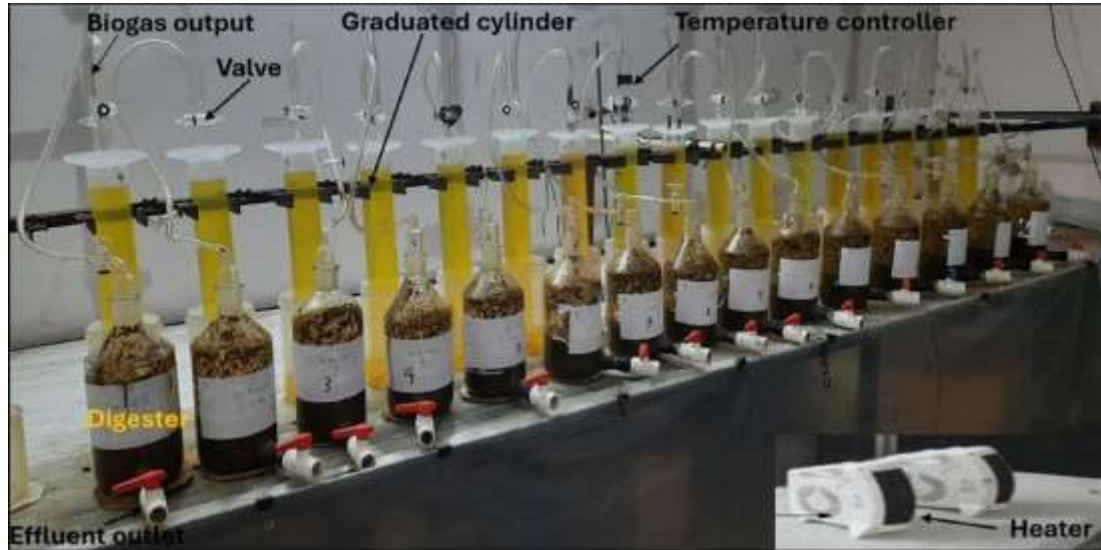


Figure 3.1: Laboratory-scale batch anaerobic digestion experimental setup for biogas production

Figure 3.1 shows the laboratory-scale anaerobic digestion experimental setup used for biogas production. The setup consists of batch digesters containing the prepared substrates, a temperature-controlled system for maintaining mesophilic conditions, gas collection units (graduated cylinders), biogas outlets, valves, and effluent outlets. The system was operated under controlled conditions to evaluate biogas generation from the co-digestion process.

Figure 3.2 shows the preparation process of the feedstock substrates before anaerobic digestion. The figure illustrates the collection, sorting, processing, and homogenisation of the substrate materials. The food waste was prepared into a suitable slurry form through

size reduction and mixing to improve substrate uniformity and enhance microbial degradation during digestion.

3.2 Feedstock Preparation

Food waste was homogenized by shredding and mixing to reduce particle size and improve slurry uniformity. Algal biomass was rinsed to remove excess sand and debris, then drained prior to digestion. Slurries were prepared using water as needed to achieve pumpable consistency suitable for batch loading. No chemical pretreatment was applied, allowing the study to isolate the effect of co-digestion under comparable operating conditions.

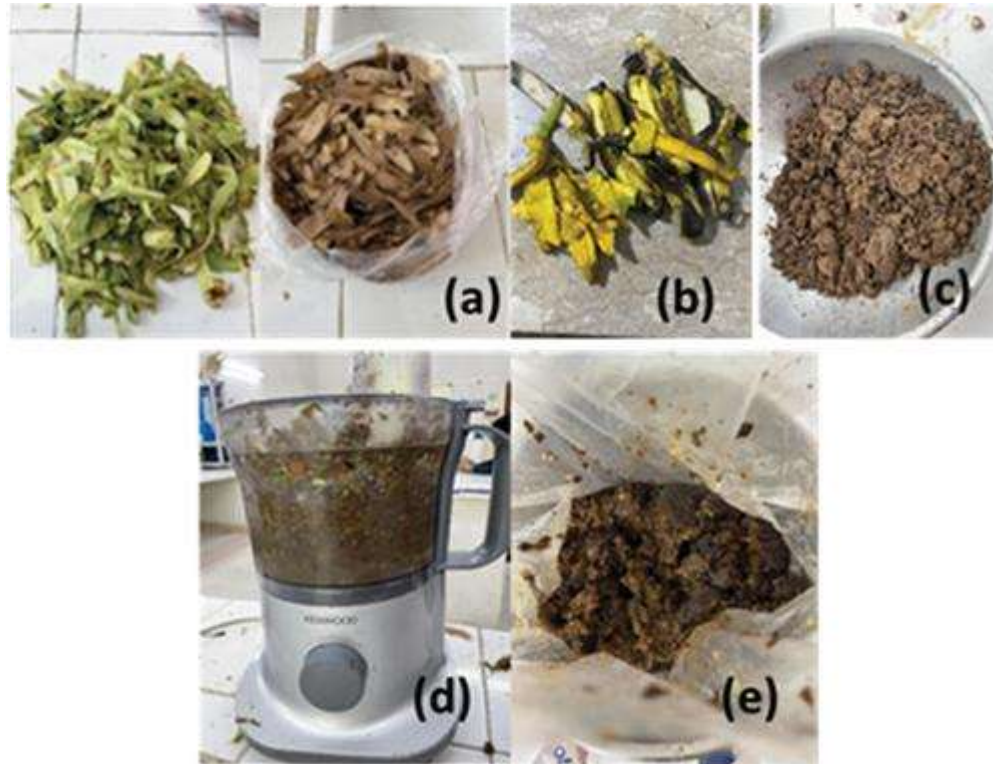


Figure 3.2: Preparation of marine algae and food waste substrates for mesophilic anaerobic co-digestion

Figure 3.2 shows the preparation process of the feedstock substrates before anaerobic digestion. The figure illustrates the collection, sorting, processing, and homogenisation of the substrate materials. The food

waste was prepared into a suitable slurry form through size reduction and mixing to improve substrate uniformity and enhance microbial degradation during digestion.

3.3 Experimental Design

Three substrate configurations were evaluated in parallel batch digesters:

Code	Description
FW	Food waste mono-digestion
AB	Algal biomass mono-digestion
FWAB	Co-digestion mixture of food waste and algal biomass

The digesters were operated in batch mode, meaning substrates were loaded at the beginning of the experiment and allowed to digest without continuous feeding. All reactors were inoculated with active

anaerobic sludge or digestate from an operating anaerobic system to provide a comparable microbial starting community.



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3.4 Reactor Configuration and Operating Conditions

The reactors were maintained under mesophilic conditions. Temperature was monitored regularly, and the system was kept within $37 \pm 1^\circ\text{C}$ throughout the digestion

period. Gas-tight reactors were connected to gas collection devices to measure cumulative biogas production. Headspace was purged during setup to minimize oxygen intrusion



Figure 3.3: Collection of marine algae feedstock for anaerobic co-digestion

3.5 Monitoring and Measurements

The following parameters were monitored during operation:

- Reactor temperature (daily or more frequently as required)
- Daily or cumulative biogas volume
- Visual observations of foaming, scum formation, and mixing behavior
- Basic process indicators such as pH, where available

Biogas volumes were normalized to the measurement conditions used consistently across all reactors. The study focused on relative yield comparison among

treatments rather than detailed methane composition analysis.

3.6 Data Analysis

Average daily biogas production was calculated for each treatment. Treatment performance was compared descriptively using mean daily gas output and cumulative gas production trends. Because the objective was operational optimization and feasibility assessment, emphasis was placed on identifying the substrate configuration that produced the highest stable gas output under identical mesophilic batch conditions.



4. RESULTS

4.1 Temperature Stability during Anaerobic Digestion

Temperature is a critical operational parameter in anaerobic digestion because microbial activity is highly

sensitive to thermal fluctuations. Throughout the experimental period, all digesters were maintained within the mesophilic temperature range of $37 \pm 1^\circ\text{C}$, ensuring favorable conditions for microbial growth and methane production.

Table 4.1. Temperature Monitoring Summary for Anaerobic Digestion Reactors

Parameter	Observation
Target regime	Mesophilic
Nominal setpoint	37°C
Observed range	$37 \pm 1^\circ\text{C}$
Operational implication	Comparable thermal conditions across FW, AB, and FWAB reactors

Table 4.1 summarizes the temperature conditions maintained throughout the experiment. The observed temperature remained within $\pm 1^\circ\text{C}$ of the target mesophilic setpoint, indicating effective temperature control. This stability minimizes the influence of thermal

variations on microbial activity and ensures that observed differences in biogas production can be attributed primarily to substrate composition rather than environmental disturbances.



Figure 4.1. Temperature Stability Profile of Experimental Digesters

Figure 4.1 illustrates the temperature profile of the reactors during the digestion period. The narrow fluctuations around the 37°C setpoint demonstrate stable operating conditions. Such stability is essential for maintaining methanogenic activity and enhancing the reliability of experimental results.

4.2 Average Daily Biogas Yield

Biogas production varied among the three treatment groups, indicating differences in substrate biodegradability and digestion efficiency.



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Table 4.2. Average Daily Biogas Yield from Different Substrate Treatments

Treatment	Average Daily Biogas Yield ($\text{m}^3 \text{ day}^{-1}$)
FW (Food Waste)	0.21
AB (Algal Biomass)	0.14
FWAB (Food Waste + Algal Biomass)	0.26

Table 4.2 presents the average daily biogas production obtained from each substrate treatment. The co-digestion treatment (FWAB) recorded the highest average daily biogas yield of $0.26 \text{ m}^3 \text{ day}^{-1}$, followed by food waste mono-digestion ($0.21 \text{ m}^3 \text{ day}^{-1}$), while algal biomass

mono-digestion generated the lowest yield ($0.14 \text{ m}^3 \text{ day}^{-1}$). These findings suggest that combining food waste with algal biomass enhanced substrate utilization and overall reactor performance.



Figure 4.2. Comparison of Average Daily Biogas Yield Among Treatments

Figure 4.2 compares the average daily biogas yields produced by the three treatment groups. The figure clearly shows that the FWAB reactor outperformed both mono-digestion systems, indicating a positive synergistic interaction between food waste and algal biomass during anaerobic digestion.

4.3 Relative Performance of Co-Digestion

To quantify the benefits of co-digestion, the percentage increase in biogas production was calculated relative to the mono-digestion treatments.



Table 4.3. Relative Improvement in Biogas Yield of FWAB Compared with Mono-Digestion Systems

Comparison	Increase in Average Daily Biogas Yield
FWAB vs FW	+24%
FWAB vs AB	+86%

Table 4.3 shows the relative performance of the co-digestion reactor. The FWAB treatment produced approximately 24% more biogas than food waste alone and 86% more biogas than algal biomass alone. These

results demonstrate the substantial advantage of combining both substrates and indicate that co-digestion enhanced biological conversion efficiency beyond what was achieved by mono-digestion.



Figure 4.3:. Percentage Increase in Biogas Yield Achieved Through Co-Digestion

Figure 4.3 presents the percentage improvement in biogas yield achieved by co-digestion. The substantial increase over algal mono-digestion highlights the limited biodegradability of algae when digested alone, while the improvement over food waste digestion indicates a beneficial synergistic effect resulting from substrate mixing.

4.4 Qualitative Reactor Performance

Distinct differences in digestion behavior were observed among the reactors throughout the experimental period.

Table 4.4. Qualitative Observations of Reactor Performance

Treatment	Observed Reactor Behavior
FW	Rapid onset of gas production and vigorous early biogas evolution
AB	Delayed gas production and relatively low overall gas generation
FWAB	Rapid startup combined with sustained biogas production throughout digestion



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Table 4.4 summarizes the qualitative observations recorded during reactor operation. Food waste digesters exhibited rapid gas evolution due to the presence of readily biodegradable organic compounds. In contrast, algal biomass digesters showed slower degradation kinetics and reduced gas production. The co-digestion reactors combined the rapid startup characteristics of food waste with prolonged gas generation, suggesting improved substrate utilization and enhanced microbial activity.

5. DISCUSSION

5.1 Enhanced Performance of Co-Digestion

The superior biogas production observed in the FWAB treatment is consistent with established anaerobic co-digestion principles. Food waste contains high concentrations of readily degradable carbohydrates, proteins, and lipids that support rapid microbial metabolism. Algal biomass contributes essential nutrients, minerals, and nitrogen-containing compounds that may enhance microbial growth and metabolic stability. The combination of these substrates likely created a more balanced digestion environment, resulting in higher biogas productivity.

The comparatively lower performance of the algal biomass treatment can be attributed to several factors, including the recalcitrant nature of algal cell walls, reduced hydrolysis rates, and the presence of mineral components that dilute the biodegradable organic fraction available for methane production.

5.2 Potential Synergistic Mechanisms in FWAB

The 24% increase in biogas production observed in FWAB relative to food waste alone suggests the presence of synergistic interactions between the substrates. Several mechanisms may explain this enhancement:

- Improved carbon-to-nitrogen (C/N) balance supporting microbial growth.
- Supply of trace elements such as magnesium, potassium, and iron required for enzymatic activity.
- Increased buffering capacity, reducing the risk of acid accumulation during fermentation.
- Complementary degradation patterns that sustain microbial activity over a longer period.

These factors collectively may have contributed to improved digestion efficiency and higher biogas yields.

5.3 Comparison with Previous Studies

The observed enhancement in biogas production through co-digestion agrees with findings reported in previous anaerobic digestion studies involving food waste combined with nutrient-balancing substrates such as manure, sewage sludge, and algal biomass. Although direct comparisons of absolute yields are difficult due to differences in operating conditions, substrate characteristics, retention times, and gas measurement methods, the positive effect of co-digestion observed in this study aligns with the broader scientific literature.

5.4 Significance of Stable Mesophilic Conditions

Maintaining reactor temperatures within $37 \pm 1^\circ\text{C}$ was crucial for ensuring stable microbial activity throughout the digestion process. Methanogenic microorganisms are particularly sensitive to temperature fluctuations, and deviations from the optimal mesophilic range can reduce methane production efficiency. Therefore, the stable thermal conditions achieved in this study strengthen confidence that the observed treatment differences resulted primarily from substrate effects rather than operational variability.

5.5 Study Limitations

Several limitations should be considered when interpreting the results:

1. Methane concentration was not measured; therefore, methane yield could not be quantified directly.
 2. Important substrate characteristics such as total solids (TS), volatile solids (VS), carbon-to-nitrogen ratio, ammonia concentration, and volatile fatty acids (VFAs) were not reported.
 3. The specific food waste-to-algae mixing ratio was not provided.
 4. Batch digestion systems may not fully represent the performance of continuously operated full-scale digesters.
 5. Variations in algal species composition and seasonal characteristics were not evaluated.
- Consequently, while the study demonstrates the effectiveness of co-digestion for enhancing biogas production, further process characterization would be required before large-scale implementation.



6. OPTIMIZATION ANALYSIS

6.1 Practical Optimization Framework

Table 6.1. Key Operational Variables for Future Process Optimization

Variable	Typical Target or Consideration
Food waste:algae ratio	Evaluate mixtures around the successful co-digestion ratio
Total solids loading	Avoid reactor overloading and excessive viscosity
Inoculum-to-substrate ratio	Maintain adequate microbial population for startup
Retention time	Balance reactor volume with substrate degradation requirements
Mixing intensity	Prevent stratification while minimizing energy consumption
Pretreatment	Assess mechanical, thermal, or chemical methods to improve algal hydrolysis

Table 6.1 identifies the major operational parameters that influence anaerobic digestion performance and should be systematically optimized in

future studies. These variables directly affect microbial activity, substrate accessibility, and reactor stability

6.2 Recommended Experimental Design

Table 6.2. Proposed Experimental Matrix for Co-Digestion Optimization

Treatment Ratio (FW:AB)	Purpose
100:0	Food waste mono-digestion control
80:20	Low algal supplementation
60:40	Moderate co-digestion
40:60	High algal inclusion
20:80	Predominantly algal substrate
0:100	Algal mono-digestion control

Table 6.2 presents a proposed substrate-ratio screening matrix for future optimization studies. Evaluating a broad range of food waste-to-algae

proportions would facilitate the identification of an optimal substrate mixture capable of maximizing methane yield and process stability.



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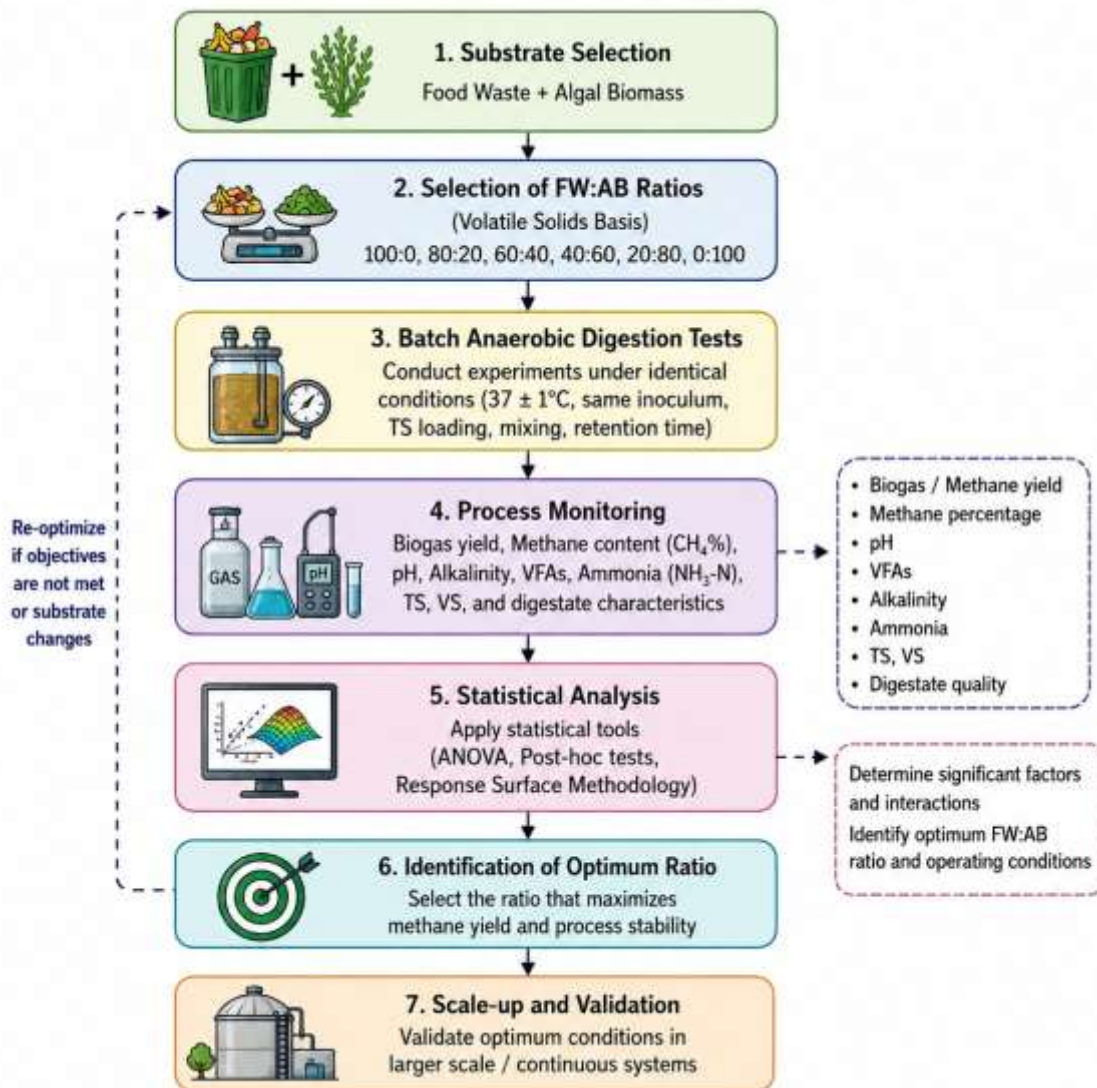


Figure 6.1. Proposed Framework for Optimization of Food Waste–Algal Biomass Co-Digestion

Figure 6.1 illustrates the recommended optimization pathway, including substrate-ratio screening, process monitoring, statistical evaluation, and identification of optimum operating conditions. This framework provides a systematic approach for improving reactor performance and supporting scale-up applications.

6.3 Statistical Considerations

Future optimization studies should incorporate replicated reactors and appropriate statistical analyses, such as analysis of variance (ANOVA) and response surface methodology (RSM). Replication is particularly



important in biological systems because inherent variability in microbial communities and substrate composition can influence digestion performance. Statistical validation would improve the reliability and generalizability of the findings.

7. Techno-Environmental Implications

7.1 Waste Management Benefits

Universities, restaurants, and institutional kitchens generate concentrated food waste streams that often incur disposal costs. Integrating these wastes into anaerobic digestion can reduce landfill disposal, odor, and greenhouse gas emissions associated with uncontrolled decomposition.

7.2 Coastal Biomass Utilization

Coastal regions may have periodic accumulations of nuisance algae or opportunities for cultivated algal biomass production. Co-digestion offers a pathway to valorize such biomass without relying exclusively on more capital-intensive biofuel conversion routes.

7.3 Digestate Reuse

The digestate produced after AD contains stabilized organic matter and nutrients that may be useful as soil amendments where regulations permit. For marine algae feedstocks, salinity and heavy metal content should be evaluated before agricultural application.

7.4 Scale-Up Considerations

For institutional deployment, continuous stirred-tank reactors (CSTRs) or plug-flow digesters would be more representative than batch systems. Scale-up should address feedstock storage, mixing energy, grit removal, corrosion resistance (especially with saline biomass), gas cleaning, and digestate handling.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

1. Stable mesophilic operation was achieved at $37 \pm 1^\circ\text{C}$ throughout the digestion period.
2. Average daily biogas yields followed the order FWAB ($0.26 \text{ m}^3 \text{ day}^{-1}$) > FW ($0.21 \text{ m}^3 \text{ day}^{-1}$) > AB ($0.14 \text{ m}^3 \text{ day}^{-1}$).
3. Co-digestion of food waste with algal biomass increased daily biogas production by approximately 24% relative to food waste mono-digestion under the tested conditions.
4. The results support the hypothesis that substrate complementarity—through improved nutrient balance, buffering capacity, and microbial support—can enhance anaerobic digestion performance.
5. Algal biomass alone showed lower biogas productivity than food waste, indicating that co-digestion is a more effective near-term utilization pathway for the tested algal material.

Main take-away

Under stable mesophilic batch digestion, co-digesting marine algal biomass with food waste produced the highest biogas output of the tested configurations, outperforming food waste alone and substantially outperforming algal mono-digestion.

8.2 Recommendations for Future Work

1. Measure methane concentration and report methane yield per unit volatile solids added.
2. Characterize TS, VS, C/N ratio, ammonia, VFAs, alkalinity, and salinity for all feedstocks and digestates.
3. Optimize the FW:AB mixing ratio using replicated experiments and response-surface methodology.
4. Evaluate mild pretreatments for algae to improve hydrolysis where economically justified.
5. Test continuous or semi-continuous reactor operation to better represent institutional-scale deployment.
6. Assess digestate suitability for land application, including salinity and trace metal analyses.



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