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Physicochemical Drivers of Methane Recovery and Techno-Economic Feasibility in Anaerobic Digestion of Organic-Rich Municipal Waste

Van Dinh Pham [1, *], Van Toi Pham [1], Minh Giang Hoang [1], Ping Yu Chang [2, 3]

1. Faculty of Environmental Engineering, Hanoi University of Civil Engineering, 55 Giai Phong Road, Hai Ba Trung District, Hanoi, Vietnam; E-Mails: dinhpv@huce.edu.vn; toipv@huce.edu.vn; gianghm@huce.edu.vn; ORCID: 0000-0003-1867-0478
2. Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan; E-Mail: cpyuntu@ntu.edu.tw
3. Water Innovation, Low Carbon and Environmental Sustainability Research Center, National Taiwan University, Taipei, Taiwan

* **Correspondence:** Van Dinh Pham; E-Mail: dinhpv@huce.edu.vn; ORCID: 0000-0003-1867-0478

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Abstract

Anaerobic digestion (AD) has emerged as a promising pathway for recovering energy from organic-rich municipal solid waste (MSW), particularly in waste systems characterized by high biodegradable content and moisture levels. However, the relationships between waste physicochemical properties, methane recovery potential, and techno-economic feasibility remain insufficiently integrated in current research. This study developed a comparative framework combining empirical prediction (S1), stoichiometric estimation (S2), and laboratory-scale AD experiments (S3) to evaluate methane recovery and energy potential from biodegradable municipal solid waste (BMSW). The analyzed waste stream contained approximately 62% biodegradable material with high moisture content and favorable C/N and VS/TS ratios for AD. Methane yields predicted by S1 and S2 reached 347 and 505 mL-CH_4/g-VS, respectively, whereas experimental digestion produced 334 mL-CH_4/g-VS under mesophilic conditions. The lower experimental yield reflected operational limitations, including incomplete biodegradation and microbial inhibition at elevated loading rates. Net electricity recovery was estimated at approximately 184-289 kWh/ton of waste, while avoided greenhouse gas emissions reached up to 1.6 ton-CO_2e/ton of waste. Capital investment analysis further indicated strong scale dependency, with larger facilities achieving substantially lower unit investment costs. Overall, the findings demonstrate that substrate physicochemical compatibility, rather than geographic context alone, governs AD performance and feasibility in organic-rich municipal waste systems.

Keywords

Anaerobic digestion; biodegradable municipal solid waste; renewable energy; greenhouse gas mitigation; circular economy

1. Introduction

Municipal solid waste (MSW) generation has increased rapidly over recent decades due to population growth, urbanization, and changing consumption patterns, exceeding 2.1 billion tons annually worldwide [1]. In many low- and middle-income countries, biodegradable organic waste remains the dominant component of municipal waste streams, often accounting for more than 50% of the total generated waste. Despite increasing attention to the circular economy and sustainable resource management, landfilling remains the primary disposal pathway in many regions, resulting in significant greenhouse gas (GHG) emissions, leachate generation, land occupation, and the loss of potentially recoverable resources [2]. Because biodegradable waste is highly susceptible to anaerobic decomposition under uncontrolled landfill conditions, municipal waste systems with high organic fractions are particularly important sources of methane emissions.

Among existing waste treatment technologies, AD has emerged as one of the most promising approaches for the valorization of biodegradable municipal solid waste (BMSW) because it simultaneously stabilizes organic matter and recovers renewable energy as biogas [3, 4]. Compared with thermal treatment technologies such as incineration, AD is inherently more compatible with wet and organic-rich waste streams due to its biological conversion mechanism [5]. High moisture content, which often reduces the efficiency of combustion-based technologies due to the additional energy required for water evaporation, may instead favor microbial degradation and methane production during AD [3, 6]. Similarly, although aerobic composting is widely applied for organic waste treatment, excessive moisture and heterogeneous substrate composition may limit oxygen transfer efficiency and process stability in large-scale composting systems [7]. Consequently, waste streams characterized by high biodegradable organic content, elevated moisture, and favorable nutrient balance are generally considered suitable substrates for AD.

The performance of AD systems strongly depends on the substrate physicochemical characteristics, particularly volatile solids (VS), total solids (TS), elemental composition, moisture content, and carbon-to-nitrogen (C/N) ratio [3, 8]. These parameters directly influence microbial activity, biodegradability, methane conversion efficiency, and process stability. Previous studies have demonstrated that waste streams with high biodegradable volatile solids content and balanced nutrient composition generally exhibit improved methane recovery potential. In contrast, lignocellulosic-rich or highly heterogeneous substrates may reduce digestion efficiency and increase operational instability [5, 8]. In addition to substrate characteristics, reactor configuration, organic loading rate (OLR), hydraulic retention time (HRT), and operational conditions also significantly affect methane production performance [5, 8].

To evaluate methane recovery potential from organic waste, several analytical approaches have been widely applied in previous studies. Stoichiometric models based on elemental composition are commonly used to estimate theoretical methane potential under ideal biodegradation conditions [5]. Empirical models derived from substrate physicochemical characteristics and operational datasets have also been developed for rapid methane prediction and preliminary feasibility assessment [3]. In parallel, biochemical methane potential (BMP) experiments provide experimentally achievable methane yields under controlled conditions and therefore offer more realistic representations of practical AD performance. However, these approaches often produce substantially different methane estimates because they reflect varying levels of theoretical assumptions, biodegradability limitations, and operational constraints.

Although numerous studies have investigated methane production from municipal organic waste, many remain limited to either laboratory-scale methane experiments or theoretical methane estimation without sufficiently integrating substrate characterization, comparative methane evaluation, and broader system implications within a unified analytical framework [5, 9]. In addition, previous research has often focused primarily on methane yield optimization. At the same time, comparatively little attention has been directed toward understanding how physicochemical waste characteristics influence the practical suitability, environmental implications, and techno-economic feasibility of AD systems. This limitation is particularly important for rapidly urbanizing regions where municipal waste streams remain highly organic-rich and moisture-dominated.

Therefore, this study proposes an integrated assessment framework to evaluate the methane recovery potential and techno-economic implications of AD in organic-rich municipal waste systems. Three complementary approaches were applied, including (i) empirical prediction based on physicochemical characteristics (S1), (ii) stoichiometric methane estimation based on elemental composition (S2), and (iii) experimental methane recovery assessment using AD systems (S3). By integrating theoretical prediction, experimental validation, and system-level interpretation, this study aims to (i) evaluate the relationship between waste physicochemical properties and methane recovery potential, (ii) compare theoretical and experimentally achievable methane yields, and (iii) assess the broader energy recovery, environmental, and techno-economic implications of AD for biodegradable municipal waste management. The findings are expected to contribute to a more realistic and transferable understanding of AD applicability in organic-rich municipal waste systems.

2. Materials and Methods

2.1 Sampling and Characterization of Biodegradable Municipal Solid Waste

BMSW samples were collected from mixed municipal solid waste streams in accordance with standardized waste characterization protocols. This reduction was systematically achieved using the Quartering Method (cone and quartering), ensuring that the six collected representative samples (50-75 kg each) remained statistically representative of the initial 600 kg bulk waste. The collected BMSW component was stored at temperatures below 4°C for further analysis.

The waste was manually sorted into major fractions (organic, plastic, paper, inert materials), and only the biodegradable fraction was retained for analysis. The sorted material was shredded to a uniform particle size (typically <20 mm) to minimize heterogeneity and improve analytical consistency. The physicochemical properties of BMSW including TS, VS, elemental composition (C, H, N, S, O), and related parameters were determined according to the current guidelines, as shown in Table 1.

Table 1 Analysis of BMSW characteristics.

No.	Characteristics	Methods
1	TS (%)	EPA 1684-2001
2	VS %)	
3	C (%)	UNI 15104
4	N (%)	UNI 15104
5	H (%)	UNI 15104
6	S (%)	ASTM Method D4239
7	O (%)	Modified EPA 440.0

2.2 Methane Yield Estimation Framework

The methodological framework consisted of three sequential levels of methane assessment: (i) empirical estimation based on physicochemical characteristics (S1), (ii) stoichiometric estimation representing theoretical methane potential under ideal conversion conditions (S2), and (iii) experimental evaluation using a continuous AD system to determine practically achievable methane recovery (S3). The resulting methane yields were subsequently used for energy recovery, greenhouse gas mitigation, and techno-economic assessments.

2.2.1 Empirical Model (S1)

Methane yield was estimated using empirical relationships between substrate physicochemical properties and methane production reported in previous AD studies [6, 10]. Correlation analysis was conducted to evaluate the relationships between methane yield and selected parameters, including pH, TS, VS, and VS/TS ratio. Linear regression analysis was subsequently applied to establish predictive relationships between substrate characteristics and methane yield. The resulting methane yield estimates were converted to theoretical energy recovery potential using the lower heating value of methane.

2.2.2 Stoichiometric Model (S2)

The AD process can be summarized using the modified Buswell equation. This equation provides a theoretical framework for calculating the amount of methane produced from a given organic substrate [10].

$$C_aH_bO_cN_dS_e+\left(a-\frac{b}{4}-\frac{c}{2}+\frac{3d}{4}+\frac{e}{2}\right)H_2O\rightarrow\left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}-\frac{e}{4}\right)CH_4+\left(\frac{a}{2}-\frac{b}{8}+\frac{c}{4}+\frac{3d}{8}+\frac{e}{4}\right)CO_2+dNH_3+eH_2S \quad (1)$$

The theoretical methane yield was corrected using biodegradability coefficients (k) obtained from published AD studies involving municipal organic waste. The corrected methane yield was used to estimate realistic methane recovery potential and associated energy production.

2.2.3 Experimental Model (S3)

A schematic diagram of the two-stage AD system used in this study is presented in Figure 1. The experimental system was designed to evaluate practically achievable methane recovery under continuous AD conditions using BMSW as substrate.

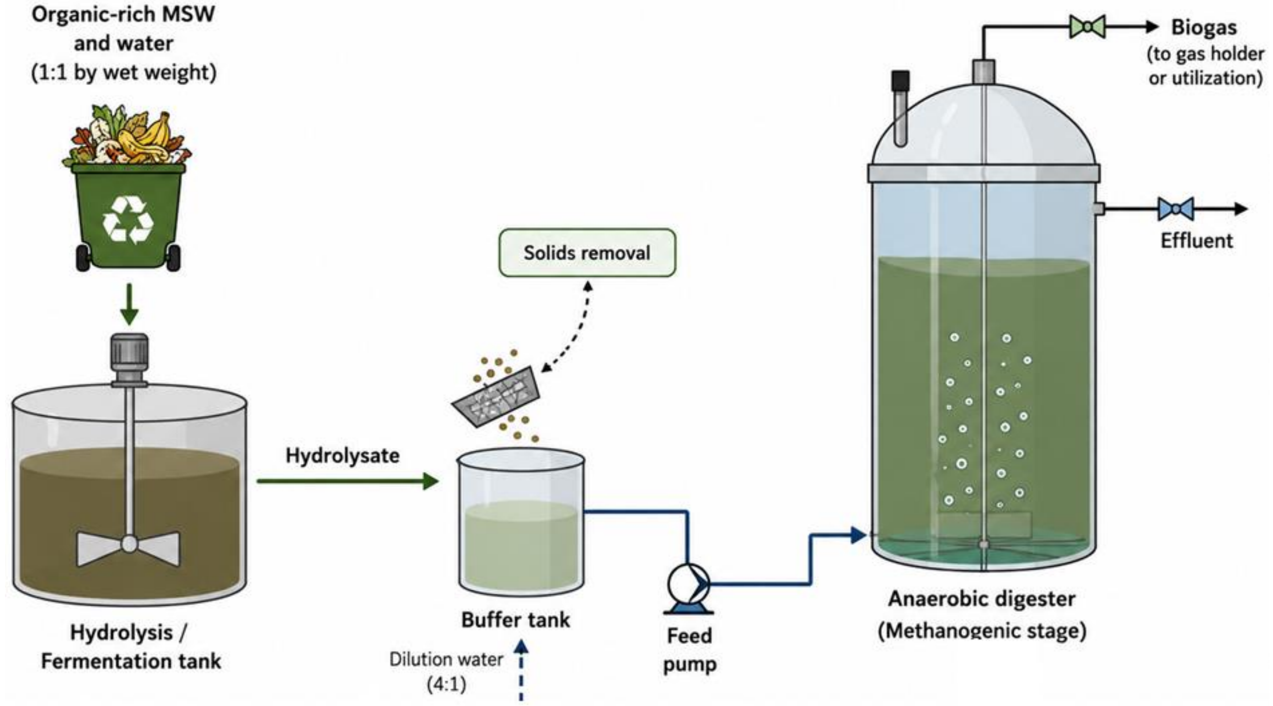

Figure 1 Schematic diagram of the two-stage AD system used in this study.

Before digestion, the collected BMSW was shredded and mixed with water at a wet weight ratio of 1:1 to facilitate substrate homogenization and wet anaerobic processing. The prepared slurry was first introduced into a continuously stirred acidification reactor operated under mesophilic conditions (35-37°C) at pH 6.5 for 5 days to promote hydrolysis and acidogenesis. After the acidification stage, insoluble materials were separated using a 1 mm filtration membrane. The resulting liquid fraction was subsequently diluted 1:4 and continuously fed into the methanogenic reactor under mesophilic conditions (35-37°C) at an OLR of 1.3, 2.6, and 5.1 g-VS/L/day. The monitoring period lasted 12 days for each OLR stage. Methane production performance was evaluated after stable reactor operation was achieved.

Biogas generated from the digestion system was collected using gas storage bags and quantified by the volumetric method. Gas composition, including methane concentration, was analyzed using a gas chromatograph (GC-2014, Shimadzu, Japan). The measured methane yield was subsequently used to evaluate experimentally achievable energy recovery and compare practical methane conversion performance with the theoretical and empirical estimation approaches (S1 and S2).

2.3 Energy Recovery Estimation

The net electricity in the system is determined using the formula $\Delta E = \Delta E_o - E_{wasted}$, where E_o is the output energy from biogas, and E_{wasted} is the electricity lost in the system to serve machinery and equipment, such as pumps, mixers, and grinders. According to Dinh and Fujiwara [11], the energy consumption in the anaerobic phase of the decomposition system is approximately 91.4 kWh/ton-TS, equivalent to 19.9 kWh/ton of waste.

The energy converted to electricity from biogas is calculated according to the formula:

$$\Delta E_o = P \times TS/100 \times VS/100 \times \xi \times \eta_m \tag{2}$$

Where:
ΔE_o: the energy converted to electricity from biogas (kWh/ton of waste),
P: Biogas yield obtained (m^3-biogas/g-VS),
ξ: Heating index of the resulting gas (35,800 kJ/m^3-CH_4),
η_m: Power conversion coefficient of biogas generator (0.35).

2.4 Greenhouse Gas Mitigation Estimation

The GHG mitigation potential of AD was estimated from two mechanisms: (i) avoidance of methane emissions from landfilling and (ii) displacement of fossil-based electricity through biogas utilization. The net GHG reduction potential was determined using the following equation (3):

$$GHG_R = GHG_L + GHG_E - GHG_{emi} \tag{3}$$

where GHG_L is avoided landfill emissions, GHG_E is avoided emissions from electricity substitution, and GHG_{emi} represents methane leakage from the AD system.

GHG_L emissions from waste degradation in landfills were estimated using the landfill emissions model [12]:

$$GHG_L = \left[\left(DOC \times DOF_f \times F_1 \times C_{CH_4} - R\right) \times (1 - OX)\right] \times GWP \tag{4}$$

where DOC is the proportion of degradable organic carbon (for organic waste, DOC = 0.15); DOC_f is the fraction of degradable organic carbon dissimilated (for organic waste, $DOC_f = 0.77$); F_1 (= 0.50) is the methane fraction of landfill gas; C_{CH_4} is the conversion rate of carbon to methane (1.34); R is the amount of landfill gas recovered or flared in the given year ($R = 0$ in this study due to the absence of gas recovery); OX is the oxidation factor (0.10 for sanitary landfill); and GWP is the global warming potential used to estimate CO_2-e from methane [13]. The figures were substituted into the formula to obtain $GHG_L = 1.60$ ton-CO_2e/ton of BMSW.

The amount of GHG emissions leaked from the biogas plant was calculated using the following formula (5) [14]:

$$GHG_{emi} = Y_{CH_4} \times (1 - CE \times DE) \times GWP \tag{5}$$

where Y_{CH_4} is the methane yield (ton-CH_4/ton); *CE* is the efficiency of biogas collection (99%); and *DE* is the efficiency of the energy recovery process (98%).

The electricity generated was supplied to the national grid. The net electricity exported from the farm was multiplied by the emission factor for electricity generation (373.6 kg-CO_2/MWh) [14].

2.5 Capital Investment Estimation

The techno-economic assessment was conducted to evaluate the influence of treatment capacity on the practical feasibility of AD systems for BMSW. The assessment focused primarily on capital investment requirements, scale-dependent cost variation, and the potential contribution of recovered electricity to operational cost offset.

Capital investment data for full-scale AD facilities treating municipal organic waste were compiled from published international studies including [9, 15, 16]. To improve comparability, all reported investment costs were converted to constant 2025 USD values using Consumer Price Index (CPI)-based normalization. The relationship between treatment capacity and total capital investment was subsequently evaluated using regression analysis.

The specific capital investment cost was calculated as:

$$C_s = \frac{C_t}{Q} \tag{6}$$

Where C_s is the specific capital investment cost (USD/ton-treatment capacity), C_t is the total adjusted capital investment cost (USD), and Q is the annual treatment capacity (ton/year).

To evaluate economies-of-scale effects, three representative facility capacities (100, 500, and 1000 t/day) were considered. Net electricity recovery was estimated based on the experimental methane yield obtained from the AD system after accounting for internal energy consumption associated with pumping, mixing, and auxiliary operations. Potential electricity revenue was estimated using the biomass electricity purchase price regulated in Vietnam under Decision No. 1008/QĐ-BCT (2025) as an example.

The techno-economic assessment was intended to provide a comparative and indicative evaluation of AD implementation feasibility rather than a complete life-cycle economic analysis. Therefore, detailed financial indicators such as net present value (NPV), internal rate of return (IRR), and carbon credit valuation were beyond the scope of this study.

2.6 Statistical Analysis

Statistical analyses were conducted to evaluate the relationships between physicochemical characteristics, methane yield, and techno-economic parameters. Pearson correlation analysis was applied to examine the associations among selected substrate properties, including pH, TS, VS, VS/TS ratio, and methane yield. Linear regression analysis was subsequently performed to evaluate predictive relationships between substrate characteristics and methane recovery performance as well as between treatment capacity and capital investment cost.

The strength of regression models was evaluated using the coefficient of determination (R^2), and statistical significance was assessed at $p < 0.05$. Statistical analyses and graphical visualizations were performed using standard statistical and spreadsheet software.

3. Results and Discussion

3.1 Characteristics of Biodegradable Waste

The composition and physicochemical characteristics of BMSW are among the most important factors governing the suitability and efficiency of biological waste treatment technologies, particularly AD. As summarized in Figure 2, the biodegradable fraction in Vietnamese municipal waste systems typically ranges from approximately 28% to 66%, depending on waste source, urbanization level, household consumption patterns, and collection practices. In the present study, the biodegradable fraction was comparable to values reported for other low- and middle-income countries such as China (47%) [17] and India (52%) [18], while remaining substantially higher than those commonly observed in high-income countries (24%) [19].

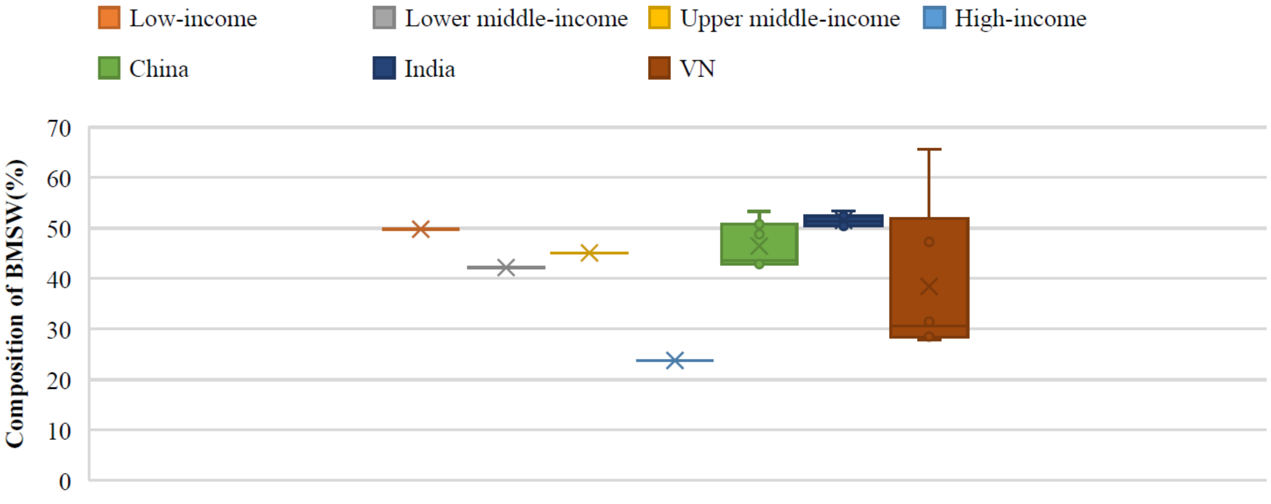

Figure 2 Comparison of biodegradable fractions in municipal solid waste across selected countries and income groups (data compiled from this study and [17-20]).

The observed variability reflects the transitional nature of waste systems in rapidly urbanizing economies. Although the organic fraction of waste generally decreases with increasing income levels, this trend is not always linear [19]. For example, upper-middle-income countries still show relatively high organic waste fractions, particularly in China, where food waste remains dominant despite rapid urbanization [17, 19]. These findings indicate that waste composition is influenced not only by economic conditions but also by dietary habits, consumption behavior, packaging intensity, and waste collection systems. Such differences in waste composition strongly affect waste management strategies and technology selection. Organic-rich waste streams, commonly observed in Vietnam, China, and India, are highly suitable for source separation and biological treatment processes due to their large biodegradable content [21]. In contrast, waste streams in many high-income countries contain higher proportions of recyclable and engineered materials, making thermal treatment and material recovery more appropriate. For instance, Japan has traditionally relied on incineration because of limited landfill capacity and well-developed thermal infrastructure. However, recent circular economy initiatives have increasingly encouraged source separation and resource recovery from biodegradable waste [19].

The physicochemical properties summarized in Table 2 further demonstrate the compatibility of the investigated waste stream with AD systems. The measured total solids (TS) content reached approximately 26%, corresponding to a moisture content of about 74%, which is typical of food-dominated municipal waste in developing Asian countries [3, 22]. Such high moisture levels may reduce incineration efficiency because considerable thermal energy is required to evaporate water [19]. Similarly, excessive moisture can negatively affect aerobic composting by limiting oxygen transfer and promoting unstable degradation conditions [6]. Although several studies have proposed co-composting strategies using low-moisture bulking agents such as rice husks, straw, and sawdust [7, 23], the scalability of these approaches is constrained by the limited availability of such materials relative to the large volume of biodegradable waste generated. This limitation helps explain the inconsistent performance of large-scale composting facilities in similar waste management contexts.

Table 2 Physicochemical properties of BMSW in Vietnam and in the world.

No.	**Parameters**	**World [3]**	**China [22]**	**Greenland [24]**	**UK [20]**	**Vietnam**	
						Vietnam [25]	**Vietnam (Current study)**
1	TS (%)	27 ± 8	18	37	24	21	26
2	VS/TS (%)	85 ± 10	62	90	91	78	67
3	TN (%TS)	3 ± 1	3	4	3	3	3
4	S (‰TS)	3 ± 2	1	1	2	NA	2
5	O (%TS)	NA	15	NA	31	NA	15
6	C/N	16	11	13	17	17	18
7	H (%TS)	7	6	NA	7	NA	5

Note: NA – Non available.

In contrast, AD is inherently a wet biological process and therefore performs more efficiently under high-moisture conditions. The measured volatile solids-to-total solids ratio (VS/TS) in the present study remained relatively high (67%), indicating that a substantial fraction of the organic matter is biodegradable and potentially convertible to methane. Although this value is lower than the global average reported by Campuzano and González-Martínez [3], it remains within the operational range commonly associated with stable methane production in mixed municipal organic waste digestion systems.

Similarly, the measured C/N ratio (17.64) falls within the generally accepted optimal range for methanogenic microbial activity (15-30), suggesting balanced nutrient conditions and relatively low risk of ammonia inhibition or carbon limitation during digestion [5]. The sulfur content also remained relatively low (2‰TS), indicating limited potential for excessive hydrogen sulfide formation during biogas production. Low sulfur content is advantageous because elevated sulfur concentrations increase gas purification requirements and may accelerate equipment corrosion during long-term AD operation.

Comparative analysis with international datasets further reveals that the physicochemical characteristics of Vietnamese BMSW are more closely aligned with organic-rich waste systems in developing Asian countries than with those of high-income regions. For example, the elevated moisture content and moderate VS/TS ratio observed in this study resemble conditions commonly reported in China and other rapidly urbanizing economies [22]. These similarities suggest that substrate physicochemical compatibility, rather than geographic location alone, is a dominant factor governing AD applicability and methane recovery performance.

Overall, the investigated BMSW exhibits physicochemical characteristics highly favorable for AD. The combination of a substantial biodegradable fraction, elevated moisture content, a balanced C/N ratio, and relatively high volatile solids content supports efficient biological methane recovery while limiting the effectiveness of alternative treatment pathways such as incineration and large-scale aerobic composting.

3.2 Biogas and Energy Potential from Digestion of BMSW

To improve the robustness and interpretability of methane yield estimation, three complementary approaches were employed: (i) empirical modeling based on physical characteristics (S1), (ii) stoichiometric estimation based on elemental composition (S2), and (iii) experimental determination using BMP tests (S3). The integration of these approaches enables not only the estimation of methane yield but also the evaluation of theoretical limits, practical constraints, and model reliability.

3.2.1 Methane Yield Based on Physical Characteristics (S1)

The relationship between selected physical parameters and methane yield is presented in Figure 3. A strong and statistically significant positive correlation was observed between TS and VS ($r = 0.92$, $p < 0.001$), indicating that VS represents the biodegradable fraction of TS. However, no significant correlation was found between methane yield and individual parameters such as pH, TS, or VS when considered independently.

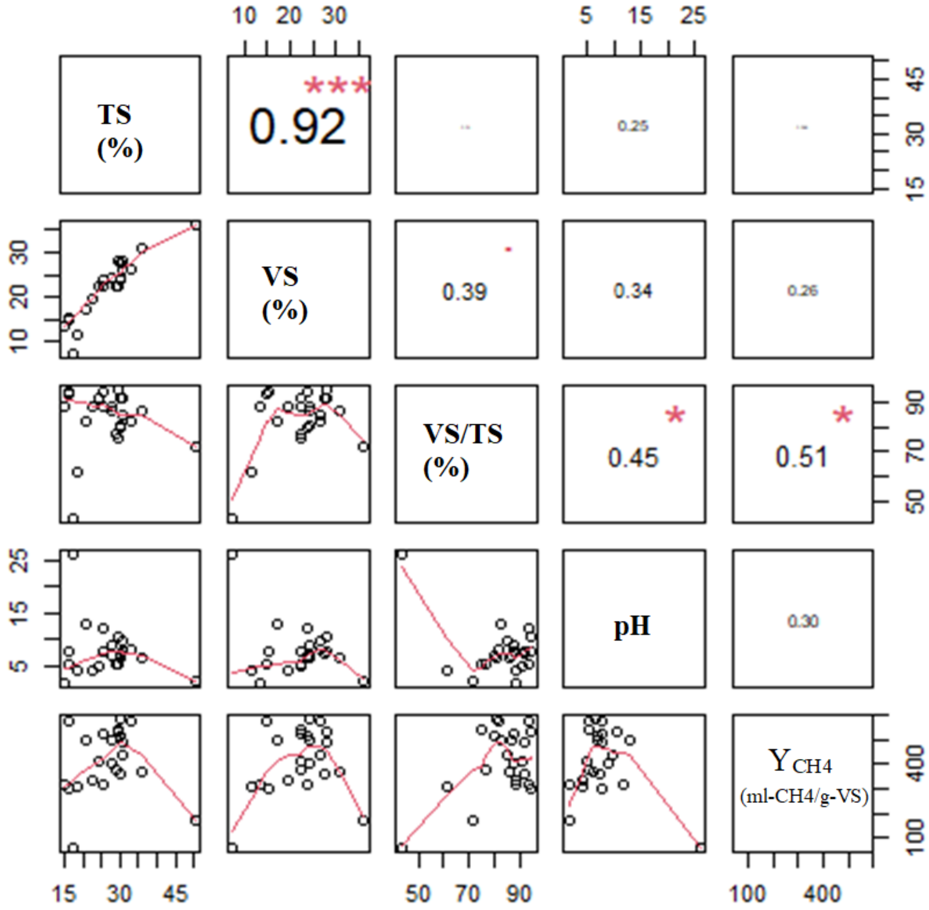

Figure 3 Correlation between physical characteristics and methane yield Y_{CH_4} (n = 27).

In contrast, the VS/TS ratio exhibited a moderate but statistically significant positive correlation with methane yield (r = 0.51, $p < 0.05$, n = 27), indicating that the quality and biodegradability of organic matter, rather than its absolute quantity, are a more reliable predictor of biogas production. A higher VS/TS ratio generally indicates a greater proportion of biodegradable organic matter available for microbial hydrolysis and methanogenesis, thereby enhancing substrate accessibility and methane conversion efficiency. A linear regression analysis yielded the following relationship: Y_{CH_4} = 5.6744 × (VS/TS) - 58.76 (ml/g-VS). Based on this model, a VS/TS ratio of approximately 76% corresponds to a methane yield of 347 mL CH_4/g-VS, equivalent to an energy output of 212 kWh/ton of waste. These values are consistent with reported ranges for organic-rich municipal solid waste systems in Asia [3, 26].

Despite its practical usefulness, this approach has inherent limitations. Empirical models do not explicitly account for microbial kinetics, inhibitory compounds, or operational instability, and therefore tend to provide optimistic estimates. Consequently, while S1 is suitable for rapid screening, its predictive accuracy for full-scale systems requires further validation.

3.2.2 Methane Yield Based on Chemical Composition (S2)

Based on the elemental composition presented in Table 3, the biodegradable fraction can be approximated by the molecular formula: $C_{797}H_{1045}O_{193}N_{39}S$. The stoichiometric conversion of this substrate yields a theoretical methane potential of 731 mL CH_4/g-VS. However, when applying an average biodegradability coefficient (k = 0.69, see Table 3), the adjusted methane yield decreases to approximately 505 mL CH_4/g-VS, corresponding to an energy recovery of 308 kWh/ton of waste. This estimate is approximately 45% higher than the empirical prediction (S1), consistent with the inherent assumptions of stoichiometric models, which is neglect process inefficiencies and assume near-complete substrate conversion. Similar overestimations have been reported in studies of agricultural and organic waste digestion [10].

Table 3 Summary of biodegradability coefficients (k).

No.	Type of technology	k	Ref.
1	Single-stage system	0.61	[27]
2	Single-stage system	0.66	[8]
3	Two-stage system	0.64	[8]
4	Three-stage system	0.76	[8]
5	Single-stage system	0.61	[28]
6	Two-stage system	0.61	[29]
7	Single-stage system	0.83	[30]
8	Two-stage system	0.82	[30]
9	Single-stage system	0.80	[10]
	Average	0.69	

It is important to note that the accuracy of this approach depends strongly on the selected biodegradability coefficient (k), which varies with reactor configuration and operating conditions. As shown in Table 3, k values range from 0.61 to 0.83. The use of an average value introduces uncertainty, particularly when extrapolating to specific systems. Therefore, calibration of k under controlled experimental conditions is necessary to improve predictive reliability.

3.2.3 Experimental Methane Yield (S3)

The experimental methane yield obtained in this study reached 334 mL CH_4/g-VS at an OLR of 1.3-5.1 g-VS/L/day, representing the achievable biodegradation performance under controlled AD conditions. This value reflects the combined influence of substrate composition, microbial activity, and operational parameters, and therefore provides a realistic indicator of methane recovery performance for mixed BMSW. When converted into energy terms, the experimental methane yield corresponds to approximately 204 kWh per ton of waste, confirming that even moderate methane production levels can provide a meaningful energy recovery pathway. However, the comparison with higher-performing systems in Figure 4 indicates a clear potential for improvement through process optimization.

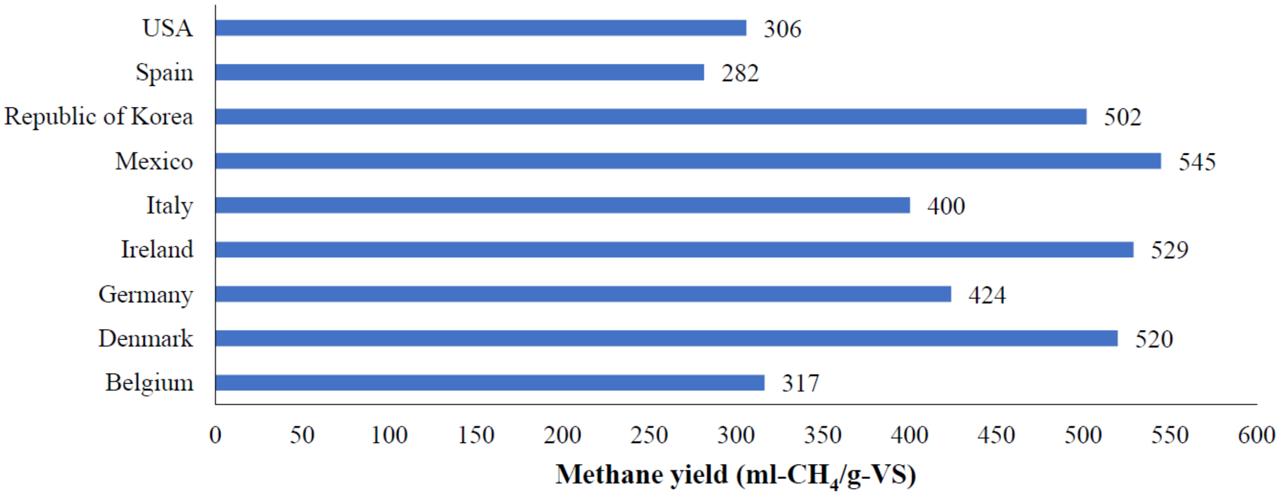

Figure 4 Methane yield from AD in different countries (Data were analyzed from raw data reported by [3]).

A direct comparison with international datasets presented in Figure 4 provides important context for interpreting this result. Methane yields reported across different countries varied considerably, ranging from 282 to 545 mL CH_4/g-VS. Within this distribution, the methane yield obtained in the present study falls in the lower–middle range, closely aligned with values reported for Belgium (317 mL CH_4/g-VS) and slightly higher than those observed in the USA and Spain. These findings suggest that the investigated system performs within the expected range for mixed municipal organic waste digestion systems. However, it does not yet achieve the higher methane recovery efficiencies reported in more optimized AD configurations.

Overall, the experimental methane yield provides a robust and realistic baseline for evaluating AD performance. When interpreted in the context of the global variability illustrated in Figure 4, this highlights both the feasibility of energy recovery from biodegradable municipal waste and the importance of process optimization to achieve higher efficiency.

3.2.4 Comparative Analysis, Reliability, and Implications

A comparison among the three evaluation approaches (S1–S2–S3) demonstrates substantial differences between theoretical methane potential and experimentally achievable methane recovery. Among the evaluated methods, S2 generated the highest methane estimates because stoichiometric calculations assume complete substrate conversion under ideal digestion conditions. In contrast, S3 provided lower but more practically representative methane recovery values because experimental systems inherently reflect operational limitations and process inefficiencies.

The observed hierarchy (S2 > S1 > S3) highlights the importance of integrating theoretical and experimental approaches when assessing AD performance for heterogeneous municipal waste systems. While theoretical models are useful for preliminary screening and resource estimation, they may overestimate practical methane recovery if substrate accessibility and operational constraints are not adequately considered. Importantly, the integrated S1–S2–S3 framework provides a more comprehensive evaluation of methane recovery potential by simultaneously accounting for substrate composition, theoretical biodegradability, and experimentally achievable conversion efficiency. Rather than relying on a single estimation approach, this framework enables a more realistic assessment of AD applicability under practical municipal waste management conditions.

These findings further support the conclusion that methane recovery performance depends not only on the quantity of biodegradable waste but also on the physicochemical quality, biodegradability, and process stability. Consequently, optimization of source separation, substrate homogenization, and operational control may be as important as feedstock quantity for improving methane recovery efficiency in municipal organic waste systems.

3.3 Energy, Environmental and Techno-Economic Implications

3.3.1 Energy Recovery Potential

To contextualize this value, estimates derived from the empirical (S1) and stoichiometric (S2) approaches indicate higher gross energy potentials of approximately 204 kWh/t and 309 kWh/t, respectively. These values define the expected and theoretical upper bounds of system performance. The observed gap of approximately 45-51% between the experimental and theoretical estimates reflects real-world inefficiencies, including incomplete biodegradation, mass-transfer limitations, and operational constraints.

As illustrated in Figure 5, the experimental system achieved lower net energy recovery than the theoretical predictions based on S1 and S2, highlighting the difference between ideal substrate conversion assumptions and practical AD performance under laboratory-scale conditions. The figure further demonstrates that energy recovery potential is strongly influenced by substrate physicochemical characteristics, biodegradability, and process efficiency. These findings support the proposed hypothesis that favorable waste composition can substantially enhance methane recovery and energy-generation potential. However, practical system limitations may reduce achievable performance compared with theoretical expectations.

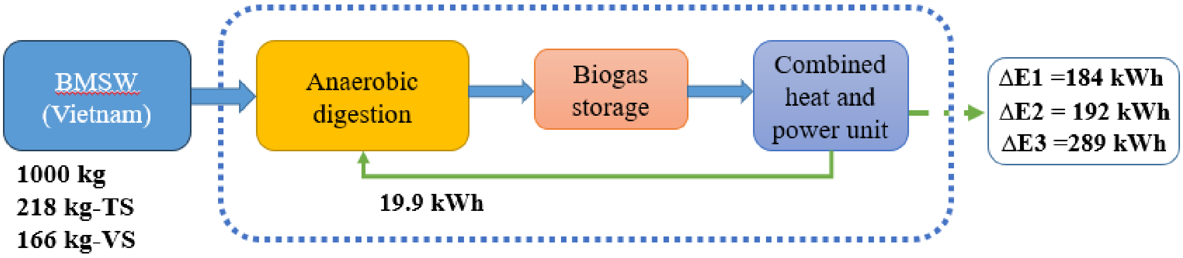

Figure 5 Energy balance in a two-stage AD system.

At a system level, even the conservative estimate of 184 kWh/t represents a meaningful energy recovery pathway for organic waste streams. For large-scale applications, this translates into substantial cumulative energy generation. However, the achievable energy output is highly sensitive to feedstock quality and process optimization. As indicated in Section 3.2, systems operating under optimized conditions such as improved waste segregation, controlled organic loading rates, and advanced reactor configurations can approach the upper range defined by S1 and S2. Therefore, the values presented here should be interpreted as a performance spectrum rather than a single deterministic outcome.

3.3.2 Greenhouse Gas Mitigation Potential

In addition to renewable energy recovery, AD offers significant greenhouse gas mitigation benefits by preventing uncontrolled methane emissions from landfills and partially displacing fossil-based electricity generation. Under conventional landfilling conditions, untreated BMSW is estimated to generate approximately 1.60 ton-CO_2e per ton of waste due to anaerobic decomposition and methane release. This result confirms that landfilling organic-rich municipal waste is a major source of GHG emissions in the development of waste management systems.

The avoided emissions from electricity displacement vary with the efficiency of methane recovery. The empirical model (S1) yields the highest electricity-related mitigation potential (0.115 ton-CO_2e/ton-waste), followed by the equilibrium model (S2) and the experimental model (S3), which generate 0.079 and 0.076-CO_2e/ton-waste, respectively. The differences reflect the variations in methane yield and the corresponding electricity recovery capacity among the three estimation methods.

Methane leakage from the AD system remains relatively low due to the assumed high collection and energy conversion efficiencies. The estimated fugitive emissions range from 0.035 to 0.053 ton-CO_2e/ton-waste. Consequently, the overall net GHG reduction potential remains consistently high across all evaluated scenarios, ranging from approximately 1.55-1.57 ton-CO_2e per ton of treated waste.

These findings indicate that the environmental benefits of AD are predominantly driven by avoiding landfill methane emissions. At the same time, electricity displacement provides a complementary but relatively smaller contribution to the total GHG mitigation. Although the differences among the methane recovery scenarios S1–S3 moderately affect energy-related emissions, the overall GHG reduction potential remains relatively stable because the avoidance of landfill methane dominates the system-level carbon balance. Overall, the results demonstrate that AD represents a promising low-carbon strategy for managing organic-rich municipal waste streams, particularly in regions where landfilling remains the predominant disposal pathway.

3.3.3 Techno-Economic Considerations

Capital expenditure remains a major barrier to implementing AD infrastructure, particularly in developing countries. Reported international datasets indicate that capital investment for AD facilities generally ranges from approximately 110-535 USD/t of annual treatment capacity in Asian countries and 350-500 USD/t in Europe and North America [20]. Based on the compiled database used in this study, the average capital investment was approximately 400 USD/t of treatment capacity, with a strong relationship observed between facility scale and total investment cost (R^2 = 0.78). As shown in Figure 6, specific capital costs decreased from approximately 373 USD/t for small-scale facilities (100 t/day) to approximately 274 USD/t for large-scale systems (1000 t/day), demonstrating significant economies of scale. Similar trends have been reported in previous techno-economic analyses of organic waste AD systems.

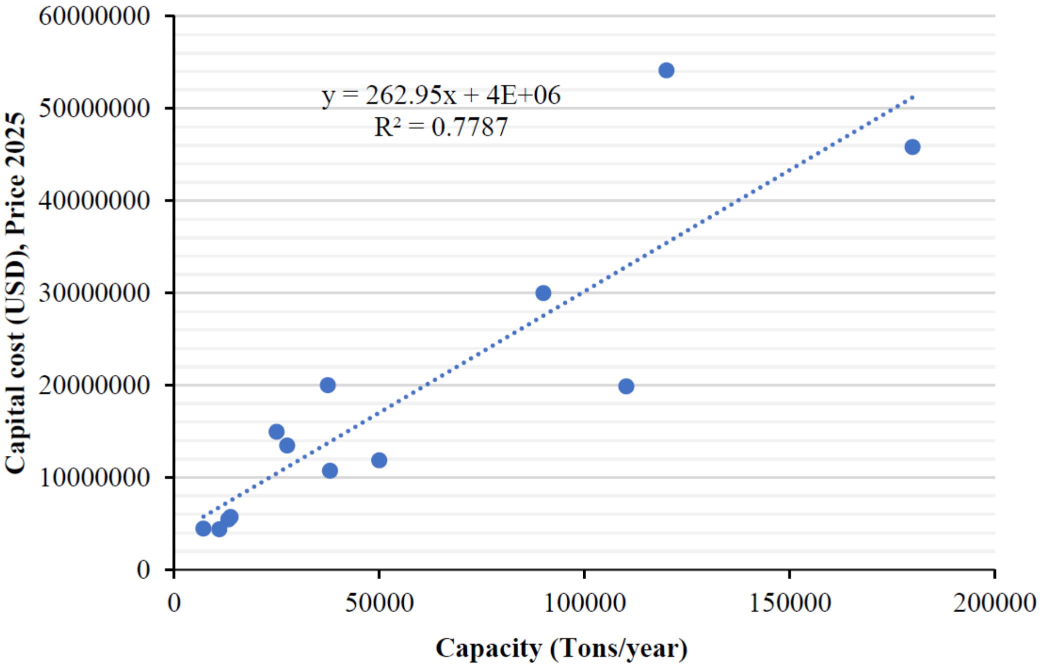

Figure 6 The relationship between capacity and total investment.

Operational expenditure is another important factor governing AD feasibility. Previous studies reported that operating costs for AD facilities in Asia typically range from approximately 20-40 USD/t of waste processed, while systems in Europe and North America generally exhibit higher operational costs of approximately 50-90 USD/t [19]. These differences are associated with labor costs, maintenance requirements, technological complexity, and process automation levels.

Based on the baseline net recoverable electricity of approximately 184 kWh/t derived from S3, the potential electricity revenue was estimated at approximately 16 USD/t of waste using the maximum biomass electricity purchase price of 2,091.74 VND/kWh (approximately 0.082 USD/kWh) established under Decision No. 1008/QĐ-BCT issued by the Vietnamese Ministry of Industry and Trade in 2025. This Vietnamese case is presented as an illustrative example within the ASEAN context. Under these conditions, electricity recovered alone could offset approximately 35–70% of the reported operating costs for AD systems in Asia. Nevertheless, the economic benefits of AD systems extend beyond electricity generation. In practical municipal waste management systems, AD facilities may also receive tipping fees for processing biodegradable waste, thereby providing an additional and relatively stable revenue stream independent of electricity market fluctuations. Previous studies have further highlighted that renewable energy incentives, feed-in tariffs, and carbon credit mechanisms substantially improve the profitability and implementation potential of AD systems [9, 16].

In addition to electricity generation, the economic viability of AD systems may be further enhanced through digestate valorization and nutrient recovery strategies within integrated circular-economy frameworks. Nevertheless, several uncertainties remain when extrapolating laboratory-scale performance to full-scale implementation. Variability in waste composition, insufficient source separation, and operational instability may reduce methane recovery efficiency and increase treatment costs under practical conditions. Therefore, although the present findings indicate that AD represents a technically feasible and potentially economically attractive strategy for managing organic-rich municipal waste, further pilot-scale and long-term techno-economic validation remains necessary to improve the reliability of full-scale implementation assessments.

4. Conclusions and Recommendations

This study evaluated the methane recovery potential from biodegradable municipal solid waste (BMSW) using an integrated framework that combined empirical prediction (S1), stoichiometric estimation (S2), and experimental AD analysis (S3). The investigated waste exhibited favorable characteristics for AD, including high organic content, elevated moisture, and suitable C/N and VS/TS ratios. Methane yields predicted by S1 and S2 reached 347 and 505 mL-CH_4/g-VS, respectively, while the experimental system achieved 334 mL-CH_4/g-VS under mesophilic conditions. The corresponding net electricity recovery potential was approximately 184 kWh/t of waste, with greenhouse gas mitigation reaching 1.55-1.57 ton-CO_2e/t of waste. The findings demonstrate that substrate physicochemical properties strongly influence methane recovery performance and AD feasibility in organic-rich municipal waste systems. Overall, the findings support the proposed research hypothesis that favorable physicochemical characteristics of organic-rich municipal waste can enable efficient methane recovery through AD with promising environmental and techno-economic performance. In addition, larger-scale AD facilities may achieve improved techno-economic performance through economies of scale.

Beyond the specific case examined, the proposed integrated assessment framework may also support broader evaluation of organic-rich municipal waste systems in other developing regions pursuing circular economy and net-zero transition strategies. Future studies should focus on pilot-scale validation, long-term operational evaluation, and further optimization of AD performance under practical operating conditions. Successful large-scale implementation of AD systems will also require supportive policy frameworks, effective stakeholder participation, and broader social acceptance to ensure long-term environmental and economic sustainability.

Future research should investigate the integration of artificial intelligence (AI), digital twins, and cyber-physical modeling frameworks to optimize AD systems under different operational and waste-composition scenarios. Such approaches may improve predictive assessment of methane generation, process stability, environmental impacts, and techno-economic feasibility, thereby supporting large-scale implementation of circular waste-management systems and sustainable energy recovery strategies [31, 32].

Author Contributions

V.D.P conducted the conceptual design, performed the experiments, analyzed raw data, and wrote the original draft. V.T.P helped analyze the data and revise the manuscript. P.Y.C and M.G.H revised the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

AI-Assisted Technologies Statement

The authors used AI-assisted language editing tools (ChatGPT, OpenAI) to improve the clarity, grammar, and academic English expression of the manuscript. The AI tools were not used to generate scientific content or interpret data. All authors carefully reviewed, edited, and verified the AI-powered text to ensure accuracy, originality, and scientific integrity, and assume full responsibility for the content of the manuscript.

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