Towards Sustainable Energy from Food Industry Sludges: Biogas Potential Assessment and Calcium-Based Additive Strategies

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Abstract. This study evaluated the biogas potential of industrial sludges from three food processing factories—chicken, dairy, and pig slaughterhouse—using Biochemical Methane Potential (BMP) tests. The effects of calcium-based additives ($Ca(OH)_2$ and $CaCO_3$) and commercial microbial consortia (B1, B2, B3) on anaerobic digestion performance were investigated. Sludge samples from grease traps were tested in 10-L batch reactors at a 1:1 (v/v) substrate-to-inoculum ratio under mesophilic conditions for 35 days. Calcium-based additives significantly enhanced biogas production, although optimal dosages varied by sludge type. The highest improvements were observed at 0.5% (w/v) Ca for chicken sludge (+45.6%), 0.7% for dairy sludge (+14.3%), and 0.3% for pig sludge (+26.3%) compared to controls. Higher calcium concentrations led to inhibition across all substrates. In contrast, commercial microbial additives showed consistently poor performance, producing low biogas yields, suggesting limited effectiveness in complex industrial sludge matrices. Kinetic models (first-order, modified Gompertz, and modified logistic) accurately described biogas production in successful treatments but failed under inhibited conditions. Overall, the findings emphasise the need for sludge-specific optimisation of calcium dosing and caution against the indiscriminate use of commercial microbial products in industrial anaerobic digestion systems.

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1 Introduction

The rapid expansion of the global food industry, driven by population growth and changing consumption patterns, has led to a substantial increase in the generation of industrial organic wastes [1]. Among these, sludges from processing units represent a major waste stream with high organic content, although their composition varies widely depending on feedstock and processing conditions [2, 3]. Inadequate management of such wastes contributes to environmental problems including water contamination, greenhouse gas emissions, and odour nuisance, thereby posing challenges to sustainability [4]. Effective treatment and valorisation of these sludges are therefore critical for both environmental protection and resource recovery [5].

Anaerobic digestion (AD) has emerged as a promising biotechnology for organic waste management, combining waste volume reduction with renewable energy generation [6, 7]. The produced biogas, rich in methane (CH_4), can replace fossil fuels and support the circular economy [8]. However, the AD of high-strength food industry sludges, particularly lipid- and protein-rich wastes, faces significant inhibition risks. Long-chain fatty acids (LCFAs) formed from lipids are toxic to methanogens, while excessive ammonia released from proteins disrupts microbial activity, leading to instability and reduced methane yields [4, 9, 10]. Such challenges compromise the technical and economic viability of AD systems [11].

To address these limitations, additive- and microbe-based strategies have been explored. Calcium-based additives, including $Ca(OH)_2$ and $CaCO_3$, can alleviate LCFA inhibition by forming insoluble calcium soaps, thereby reducing LCFA toxicity, while also enhancing digester buffering capacity [3, 8, 11]. In parallel, commercial microbial consortia targeting lipid degradation have gained attention as potential enhancers, though their effectiveness remains highly substrate- and condition-dependent [12, 13].

This study evaluated the biogas potential of diverse real-world food industry sludges (chicken, dairy, and pig slaughterhouse) using Biochemical Methane Potential (BMP) assays [14]. The objectives were to examine the role of mixed calcium-based additives in overcoming inhibitory factors and to assess microbial consortia (B1–B3) as alternative enhancers. Biogas production data were analysed with kinetic models—First-order, Modified Gompertz, and Modified Logistic—to elucidate digestion kinetics and quantify additive impacts [15, 16]. The findings provide insights into tailored additive strategies for efficient and sustainable AD of complex food industry wastes.

2 Methods

This study employed Biochemical Methane Potential (BMP) tests to evaluate the biogas production potential from various industrial sludges and the efficacy of different chemical and microbial additives.

2.1 Substrate and inoculum

Sludge samples (substrate) were collected from the grease traps of three distinct food processing factories in Thailand: a chicken processing plant (Factory 1), a dairy processing plant (Factory 2), and a pig slaughterhouse and fresh pork cutting facility (Factory 3). The collected sludge samples were stored at 4°C prior to use to minimize biological activity.

The inoculum used for the BMP tests was anaerobic sludge obtained from a full-scale biogas digester at a chicken processing plant. The Substrate to Inoculum (S/I) ratio was maintained at 1:1 by volume for all experiments. Initial characteristics of the raw sludge from each factory and the inoculum, including Total Solids (TS), Volatile Solids (VS), pH, and Alkalinity, were analyzed.

2.2 Additives

Calcium-based additives were prepared by mixing calcium hydroxide ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$) at a 1:1 ratio by weight. These mixed calcium additives were applied at various concentrations of 0.3%, 0.5%, 0.7%, and 1.0% (w/v).

Commercial lipid-degrading microbial consortia (B1, B2, B3) were used in powder form. Prior to addition into the reactors, these powdered consortia were pre-conditioned by being reconstituted in wastewater collected directly from the respective factories. The concentrations used for the B-series additives were 0.05% and 0.25%.

2.1 Experimental setup

The BMP tests were conducted using 10-L reactors in a batch mode. A diagram of the experimental setup is presented in Fig. 1. Each experimental condition was run in triplicates (3 replicates). The reactors were operated under mesophilic conditions (approximately 37∘C) and incubated for 35 days. No mechanical mixing was applied during the digestion period. The pH levels were monitored but not adjusted throughout the experiment.

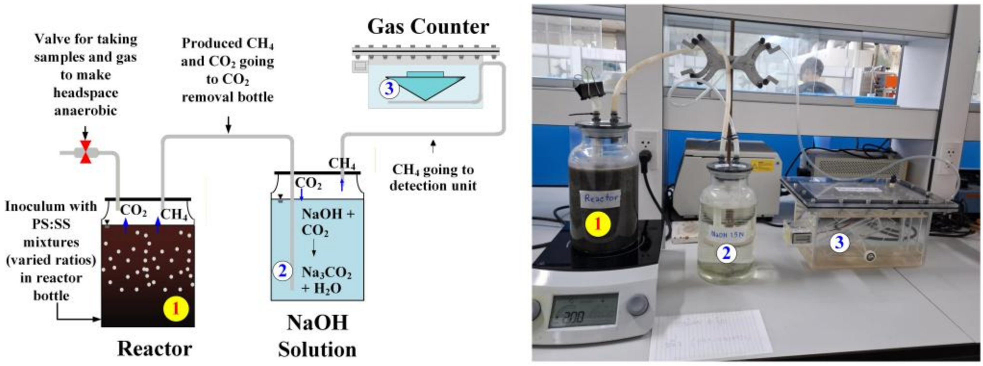

Fig. 1. BMP test setup: (1) reaction tank, (2) NaOH trap, and (3) gas collection container

3 Results and discussion

3.1 Biogas production from chicken processing sludge (factory 1) and impact of calcium-based additives

3.1.1 Accumulated biogas production

The accumulated biogas production profiles for chicken processing sludge are shown in Figures 2, demonstrating the effects of additive applications on digestion performance. In the control (0% Ca), cumulative production reached approximately 285,000 mL after 35 days. The application of calcium-based additives markedly enhanced biogas yield, particularly at lower concentrations. The optimal outcome was observed at 0.5% Ca, producing about 415,000 mL—an increase of 45.6% relative to the control. Similarly, 0.3% Ca achieved approximately 375,000 mL, representing a 31.6% increase. These results confirm the effectiveness of calcium in enhancing methane recovery from chicken processing sludge, which is rich in fats and proteins and thus prone to inhibition by long-chain fatty acids (LCFAs) and ammonia [4]. Calcium ions alleviate LCFA toxicity through the formation of insoluble calcium soaps, reducing their bioavailability, while also stabilising pH by providing buffering capacity [3, 8].

At higher concentrations, however, calcium exerted inhibitory effects. Treatments with 0.7% Ca and 1.0% Ca yielded only ~22,000 mL and ~26,000 mL of biogas, respectively, far below both the control and the lower Ca levels. This suggests the presence of an optimal concentration window, beyond which calcium impedes digestion. Potential mechanisms include nutrient precipitation (e.g., phosphates), elevated alkalinity disrupting microbial activity, and formation of insoluble compounds limiting mass transfer [3, 8].

In contrast, the B-series microbial consortia (B1–B3) performed poorly at both 0.05% and 0.25%. The best case, 0.25% B3, produced only ~45,000 mL, less than 20% of the control. Several treatments, such as 0.05% B2 and 0.05% B3, yielded <5,000 mL, with flat profiles indicating negligible methanogenesis. This underperformance highlights the limited efficacy—or potential inhibition—of these additives under the tested conditions. Their ineffectiveness may reflect an inability of introduced strains to compete with indigenous microbes, sensitivity to inhibitors, or insufficient acclimation [12].

Overall, calcium demonstrated a robust and immediate enhancement mechanism, through chemical and physical pathways, while microbial consortia were largely ineffective. These findings underscore calcium's practical potential as a reliable additive for improving anaerobic digestion of lipid-rich chicken processing sludge [3, 8].

3.1.2 Kinetic modeling of biogas production

Figure 2 illustrates the fitting of experimental accumulated biogas data to three common kinetic models: First-order, Modified Gompertz, and Modified Logistic. The ability of these models to describe the observed biogas production kinetics varied significantly across the different additive treatments. For the control (0% Ca) and the successful calcium treatments (0.3% Ca and 0.5% Ca), all three models generally provided a good fit to the experimental data, especially during the initial and exponential phases of biogas production. The curves from the First-order, Modified Gompertz, and Modified Logistic models closely followed the experimental data, indicating that the underlying biological processes were well-described by these conventional models for batch anaerobic digestion [15]. This suggests a relatively smooth and uninhibited digestion process under these conditions, characterized by distinct lag, exponential, and stationary phases.

However, for treatments with higher calcium concentrations (0.7% Ca, 1.0% Ca) and all B-series additives, the model fitting was considerably less accurate. In these cases, the experimental data points often showed very limited or no significant biogas production, appearing as flat lines near the x-axis. Consequently, the kinetic models, which are designed to capture sigmoidal or exponential growth patterns, struggled to accurately represent these inhibited or dormant digestion profiles [15]. The deviations between the predicted and experimental data were pronounced, particularly where biogas production was minimal (e.g., 0.05% B2, 0.05% B3, 0.7% Ca, 1.0% Ca). This indicates that the anaerobic digestion process under these conditions was either severely inhibited or did not proceed effectively, rendering the typical kinetic models less applicable due to the lack of a discernible production curve. The inability of the models to fit these inhibited conditions further reinforces the conclusion that the B-series microbial additives, as applied, did not successfully stimulate biogas production from chicken processing sludge.

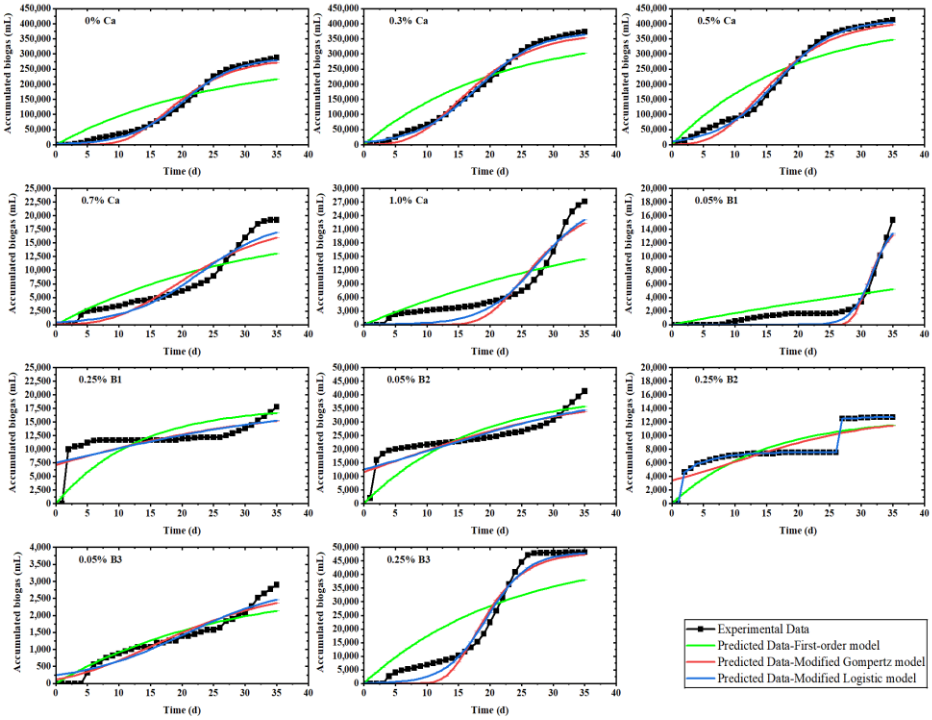

Fig. 2. Kinetic modeling of biogas production from chicken processing sludge

3.2 Biogas production from dairy processing sludge (factory 2) and impact of calcium-based additives

3.2.1 Accumulated biogas production

The accumulated biogas production profiles for dairy processing sludge are presented in Figures 3. In the control (0% Ca, 12:1), cumulative production reached ~28,000 mL over 35 days, showing a sigmoidal batch AD pattern. Calcium-based additives significantly affected outcomes. The 0.7% Ca (12:1) treatment achieved the highest yield, >32,000 mL, a 14.3% increase compared with the control. In contrast, 0.3% Ca (12:1) and 0.5% Ca (12:1) produced only ~1,700 mL and ~250 mL, indicating inhibition or delayed digestion at these levels. These findings suggest a distinct dose-response relationship compared with chicken sludge, where lower Ca levels were more effective. The mechanism may involve calcium mitigating ammonia and LCFA inhibition arising from the high protein and fat content of dairy sludge [4]. Calcium ions precipitate LCFAs, reducing toxicity and stabilising digestion [3, 8].

At 1.0% Ca (12:1), production dropped to ~1,800 mL, supporting the concept of an optimal Ca range, with overdosing causing inhibition due to nutrient precipitation, pH imbalance, or ionic stress [3, 8]. Control tests further showed substrate-to-inoculum ratio effects: 0% Ca at 8:1 yielded ~900 mL, while 6:1 produced ~27,500 mL. The commercial microbial additive (0.25% B3, 12:1) performed poorly (<2,000 mL), consistent with chicken sludge results, likely due to poor adaptation of introduced strains [12]. Overall, calcium improved digestion at optimal concentrations, while under-/overdosing and microbial additives hindered performance.

3.2.2 Kinetic modeling of biogas production

Figure 3 illustrates the fitting of accumulated biogas production data from dairy sludge to three kinetic models: First-order, Modified Gompertz, and Modified Logistic. The adequacy of these models varied among additive treatments and OLRs. For the control (0% Ca, 12:1), 0.7% Ca (12:1), and 0% (6:1), all models closely followed the experimental curves, particularly during the initial and exponential phases, confirming their suitability for successful digestion runs and the ability to describe conventional batch AD processes [15].

In contrast, treatments with low or negligible production—0.3% Ca (12:1), 0.5% Ca (12:1), 1.0% Ca (12:1), 0.25% B3 (12:1), and 0% (8:1)—showed poor model agreement. Their flat or near-linear trends deviated strongly from the sigmoidal predictions, underscoring the inhibitory effects of inappropriate calcium dosages and the ineffectiveness of B-series additives. These results highlight that while standard kinetic models effectively capture well-performing digestion, they fail to represent inhibited or dormant profiles, reflecting the limitations of AD under unfavourable conditions.

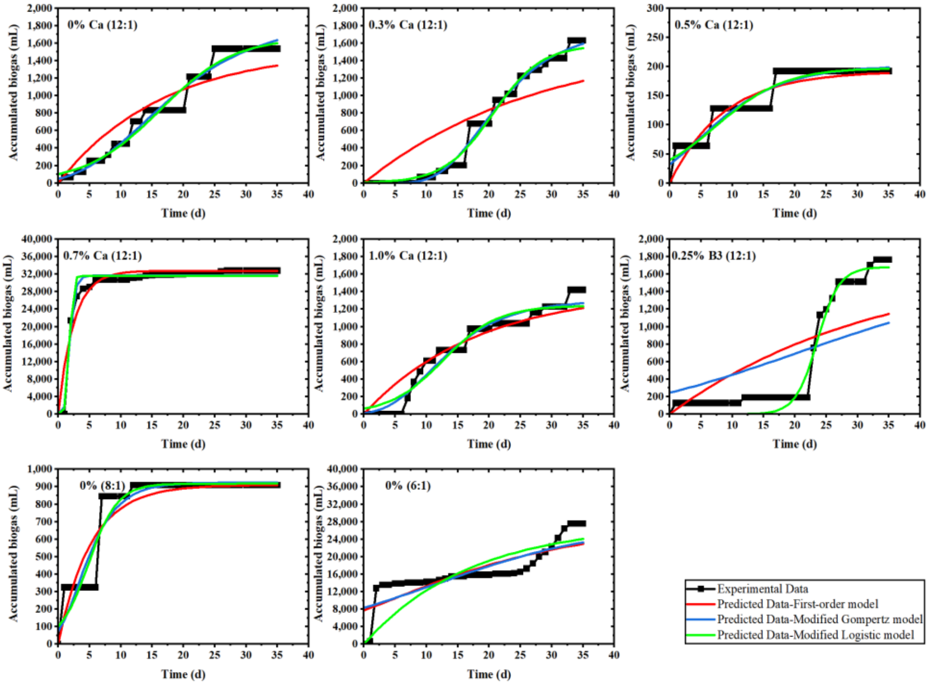

Fig. 3. Kinetic modeling of biogas production from dairy processing sludge

3.3 Biogas production from pig slaughterhouse and fresh pork cutting sludge (factory 3) and impact of additives

3.3.1 Accumulated biogas production

The accumulated biogas production profiles for pig slaughterhouse sludge (Factory 3) are shown in Figures 4. In the control (0% Ca), cumulative production reached ~285,000 mL over 35 days, following a typical sigmoidal digestion curve. Calcium-based additives significantly enhanced performance at intermediate concentrations. The best outcome was observed at 0.5% Ca, yielding ~415,000 mL, a 45.6% increase compared with the control, while 0.3% Ca also performed strongly, producing ~375,000 mL (31.6% increase). These improvements are particularly relevant for slaughterhouse sludge, which is rich in fats and proteins. Calcium mitigates LCFA inhibition by forming insoluble calcium soaps, lowering toxic LCFA concentrations, and contributes buffering capacity to stabilise pH, crucial for methanogenesis in protein-rich substrates prone to ammonia accumulation [3, 4, 8].

By contrast, higher Ca concentrations were detrimental. Treatments with 0.7% Ca and 1.0% Ca yielded ~22,000 mL and ~26,000 mL, respectively, far below both the control and optimal doses. Such inhibition may arise from nutrient precipitation (e.g., phosphates), disruption of microbial activity due to elevated ionic strength, or formation of precipitates that hinder mass transfer [3].

The B-series microbial consortia (B1–B3), tested at 0.05% and 0.25%, consistently underperformed compared with both the control and calcium treatments. The best result, 0.25% B3, produced ~45,000 mL (<20% of control), while several treatments (e.g., 0.05% B1, B2, B3) yielded <5,000 mL. These outcomes suggest ineffectiveness or inhibition when applied to slaughterhouse sludge. The exogenous strains likely failed to establish within the complex microbial community or were inhibited by waste characteristics such as high protein or blood content [12]. The flat profiles across B-series treatments confirm minimal methanogenic activity, underscoring the limited utility of such additives for this substrate.

3.3.2 Kinetic modeling of biogas production

Figure 4 shows the fitting of accumulated biogas data from Factory 3 sludge to three kinetic models: First-order, Modified Gompertz, and Modified Logistic. Model performance varied across treatments. For the control (0% Ca) and effective calcium applications (0.3% Ca, 0.5% Ca), all three models fitted the data well, particularly during the lag and exponential phases. The predicted curves closely matched the experimental profiles, indicating that the digestion process proceeded smoothly and could be adequately described by conventional batch AD models [15].

By contrast, treatments with higher calcium concentrations (0.7% and 1.0% Ca) and all B-series additives showed poor agreement. Experimental data exhibited flat or near-linear profiles with minimal biogas production, which conventional models failed to capture. Since these models are designed to represent sigmoidal or exponential growth, their poor performance reflects the inhibited or dormant state of digestion under these conditions, where no clear production curve developed [15].

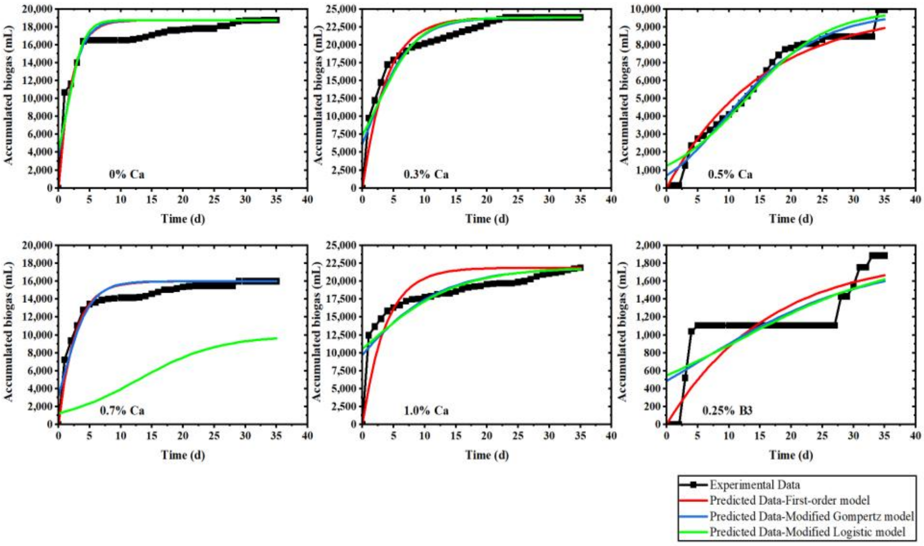

Fig. 4. Kinetic modeling of biogas production from pig slaughterhouse and fresh pork cutting sludge

4 Conclusions

This study successfully demonstrated the varying impacts of calcium-based additives and commercial microbial consortia on the biogas potential of real-world food industry sludges. Calcium-based additives significantly enhanced biogas production, with optimal concentrations (ranging from 0.3% to 0.7% w/v) being highly dependent on the specific sludge type, highlighting the need for tailored applications. Conversely, commercial lipid-degrading microbial consortia consistently proved ineffective across all tested sludges, indicating their limited applicability in complex industrial waste matrices. While kinetic models effectively described successful digestion, they struggled with inhibited conditions. These findings emphasize that optimizing additive strategies for anaerobic digestion requires specific consideration of waste characteristics to ensure efficient biogas recovery and sustainable waste management.

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