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Enhancing the efficiency of biogas production from organic waste through the blending of various types of treated leachate in different proportions

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ABSTRACT

The management of landfill leachate continues to provide a significant environmental issue owing to its elevated organic load, low biodegradability, and the presence of hazardous substances. This study investigated the enhancement of biogas production efficiency through anaerobic co-digestion of organic waste with different proportions of mature landfill leachate (ML) and pretreated mature leachate by the adsorption process (TA). Durian shell-derived activated carbon was prepared and applied to pretreat mature leachate prior to anaerobic digestion. In experiment I, the liquid mixture of distilled water (W) and mature leachate (ML) was varied as 100:0, 75:25, 50:50, 25:75, and 0:100, which was based on volume. Biochemical methane potential (BMP) assays were conducted under mesophilic conditions (35 ± 1 °C) for 50 days to evaluate methane yield and organic matter removal efficiency. The result of this study indicates that the liquid mixture of 75% distilled water and 25% mature leachate (W75:ML25) had the highest methane production and organic removal efficiency. Adding mature leachate to the system could reduce the lag phase and improve buffering capacity. However, higher mature leachate proportions (>25%) reduced methane yield due to inhibitory substances. In experiment II, the liquid mixture ratios of mature leachate (ML) to treated mature leachate by adsorption (TA) were varied as 100:0, 75:25, 50:50, 25:75, and 0:100, based on volume. The liquid mixture of 25% mature leachate and 75% treated leachate by adsorption (ML25:TA75) produced the highest methane accumulation and organic removal efficiency. Pre-treatment of mature leachate by the adsorption process could improve leachate quality and further enhanced anaerobic digestion performance.

Keywords: anaerobic digestion, mature leachate, biogas production, organic waste.

INTRODUCTION

The continued expansion of cities in various countries around the world has led to an increase in the amount of municipal solid waste (MSW). Poor waste management has a significant impact on the global and local environment and human health. The landfill method has been widely used for MSW disposal, although it generates a heavy burden of high-strength wastewater known as leachate. MSW leachate has some unique characteristics, which depend on multiple factors, such as the stage of landfill aging, the composition of the waste, the hydrological conditions, and the height of the landfill cell (Youcai, 2018; Beinabaj et al., 2023). Normally, leachate has a high organic concentration. The COD concentration, which is varied based on the leachate maturity, is around 4.000–20,000 mg/L (Kurniawan et al., 2006). The composition of pollutants is complex, and the leachate quality is of considerable variation. The leachate contains more than hundreds of organic pollutants, most of which are humic carbohydrates and fulvic acids. The leachate also contains some non-degradable substances (PAHs, phenolic compounds, alcohols, aniline compounds, and heterocyclic aromatic compounds) and heavy metals (Youcai, 2018; Beinabaj et al., 2023). Consequently, leachate may pose adverse effects on the environment and public health if discharged to water bodies without appropriate treatment due to its composition (Ferraz and Yuan, 2020). Recirculation to the landfill body and drainage to wastewater treatment plants are practically used (Hendrych et al., 2019). Biological processes (aerobic or anaerobic), chemical and physical processes (adsorption, chemical oxidation, and coagulation-flocculation), and a combination of physical-chemical and biological processes have been used for leachate treatment according to different leachate quality and composition (Chelliapan et al., 2020). Biological treatment has been extensively applied to leachate treatment in recent years due to its high organic removal efficiency and cost-effectiveness. Stabilization ponds, which are considered simplified treatment systems, have been applied for leachate treatment in tropical countries (Frascari et al., 2004). However, biological treatment suffers from the non-biodegradable compounds, heavy metals, and elevated ammonium concentration that are contained in the leachate (Kamal et al., 2022). Then, biological treatment alone is not effective to treat the mature landfill leachates (old leachate) that contain various low biodegradable compounds (Ghahrchi and Rezaee, 2021). Adsorption, which is a physical or chemical treatment, has been reported as an effective method for removing high-molecular-weight compounds and heavy metals from the leachate. Commercial activated carbon, which is a conventional adsorbent, is widely applied in the treatment process (Norashiddin et al., 2019). Powder-activated carbon (PAC) and granular-activated carbon (GAC) could remove 89.2% and 73.4% of hydrophobic organic chemicals, respectively (Liyan et al., 2009). Adsorption treatment is more suitable to treat old leachate with COD removal of 69% compared with chemical precipitation (27%) and coagulation/flocculation (10–25%) (Liu et al., 2017). Nevertheless, leachate treatment by the adsorption process is limited due to high production costs and expensive carbonaceous material. In the last few decades, local agricultural waste and industrial by-products have been used to prepare activated carbon through physical or chemical activation to address this issue. Foo et al. (2013), who investigated leachate treatment by using tamarind fruit activated carbon, reported that maximum NH_3-N and COD were 91.23% and 79.83%, respectively. More than 90% of color and COD were removed by using spent coffee grounds activated carbon (Ferraz and Yuan, 2020). Nevertheless, the adsorption efficiency depends on the type and concentration of pollutants, adsorbent material, and environmental conditions (Rathi and Kumar, 2021). Organic material, which is the main contributor to municipal waste (44% of global MSW), has good potential for biogas production from anaerobic digestion (Ibarra-Esparza et al., 2023). However, high substrate content may cause inadequate mixing, leading to the accumulation of volatile fatty acids (VFAs), which can reduce pH and biogas production; additionally, the unbalanced nutrient composition of organic waste is a significant limiting factor for anaerobic digestion (Alzate et al., 2012). Then, anaerobic co-digestion (AcoD) is an option to improve the process efficiency. AcoD is the digestion of two or more substrates with complementary characteristics, which shows better performance and provides better nutrient balance and biogas yield than mono-digestion (Lv et al., 2021). Previous research reported that leachate can be used as a co-substrate with organic waste in anaerobic digestion according to the rich ammoniac nitrogen and trace metal concentrations (Montusiewicz, 2014; Xiaofeng et al., 2014; Lv et al., 2021). The high content of ammonia nitrogen in leachate can amend the buffering ability, and the rich trace metal in leachate can supply the nutrients for anaerobic bacteria in anaerobic digesters. Moreover, the mass transfer of wet anaerobic digestion can be enhanced by adding the leachate, which can dilute the effect of high suspended solid concentration in the digester (Lv et al., 2021). Biogas production from the co-digestion of organic waste and leachate could be enhanced by blending mature and young leachate; the amount of biogas produced could vary from 19% to 41%, depending on the ratio of combining mature and young leachate (Nair et al., 2014). However, the process of anaerobic digestion is sensitive to high levels of toxic compounds such as heavy metals, phthalate esters, linear alkylbenzene sulfonates and free ammonia (Fountoulakis et al., 2008). Consequently, leachate that consists of a high concentration of pollution requires combined treatment techniques to improve anaerobic process efficiency. Fazzino et al. (2021), who applied the combination processes of active filtration (zero-valent iron (ZVI) mixed with lapillus and ZVI mixed with granular activated carbon) and anaerobic digestion to treat mature landfill leachate, found that the treatment efficiencies of the anaerobic digestion increased when the leachate was pre-treated with active filtration. Although recent studies have reported that the landfill leachate can be treated by agricultural waste adsorbents and anaerobic digestion, the literature is still lacking the application of the anaerobic digestion combined with the adsorption process for leachate treatment. The main objective of this study was to enhance the biogas generation from anaerobic co-digestion of organic waste with different proportions of pretreated landfill leachate.

MATERIALS AND METHODS

Organic waste and leachate sampling

Organic waste was used for this study from the different households. The organic waste fractions were made up of cooked white rice, meat, vegetables, and fruit peel. The organic waste was grinded to reduce the size and homogenous by grinder and then store at 4 °C until being used. Characterization of organic waste was shown in Table 1.

The leachate used in this experiment was directly collected from an old sanitary landfill in Thailand (operated for more than 15 years). The leachate treatment system applied in this landfill was a stabilization pond system. The stabilization pond consisted of an anaerobic pond, a facultative pond, aerobic ponds and a mature pond that were connected in series. The raw leachate and the mature leachate (ML) were collected from the collection pond and the 4th pond of the stabilization pond, respectively. All physical and chemical characteristics of leachate were analyzed in triplicate using standard methods. Characteristics of the raw leachate and the mature leachate were shown in Table 2.

Table 1. Characterization of organic waste

Parameter	Organic waste
MC (%)	71.34±3.57
TS (%)	28.66±3.57
VS (%)	24.55±3.01
VS/TS	85.67±1.38
pH	7.05±0.38
C (%)	46.20
N (%)	1.89
C/N Ratio	24.44

Activated carbon preparation

In this experiment, durian peel was used as the precursor for durian shell-derived activated carbon (DAC) preparation. Durian shells were collected from the market in Rayong province, Thailand. The DAC preparation method was modified from Jaikua et al. (2026) and Chandra et al. (2009). The durian shell was repeatedly rinsed with distilled water, chopped into small pieces, and dehydrated in an oven at 105°C overnight, then subjected to sieving using a sieve shaker to obtain particle sizes between 2 and 4 micrometers. In order to produce the activated carbon, the dried durian shell was mixed with phosphoric acid (H_3PO_4) solution (70%) at 0.2 of the impregnation ratios (durian shell to H_3PO_4). The impregnation was conducted in a 250 mL Erlenmeyer flask and placed in the orbital shaker (250 rpm) for 24 h at room temperature. The mixture was thereafter poured onto the porcelain disc, rinsed with distilled water until the pH reached between 6.5 and 7.0, and dried at 105 °C for 24 hours in the oven. The dried product was subsequently placed in the furnace at 800 °C for 1 hour and then stored in a desiccator.

Protocol for treating leachate by adsorption

The adsorption process was performed at optimum conditions as the best conditions for COD removal that were obtained from the pre-test. Preparation of the treated mature landfill leachate by adsorption (TA) was described as follows. The DAC was put into the 50 ml of the mature landfill leachate. The batch experiment was conducted in a 250 mL Erlenmeyer flask and placed in the orbital shaker (250 rpm) for 4 h at room temperature. After adsorption for a pre-determined time, the solution was separated from the adsorbents with a filter, and the characteristics of the aqueous sample (treated leachate by adsorption) were analyzed and shown in Table 2. The treated leachate was stored at 4 °C prior to its use for the experiments.

Experimental design

The enhancement of anaerobic digestion of organic waste using biochemical methane potential (BMP) experiments at varying amounts of treated leachate was conducted utilizing batch methods. The batch experiment was divided into two parts, labelled I and II. Table 3 illustrates the

Table 2. Characteristics of the raw leachate, mature leachate and treated leachate

Parameter	Raw leachate	Mature landfill leachate (ML)	Treated mature landfill leachate by absorption process (TA)
Turbidity (NTU)	466±10.10	355±2.56	269.80±0.16
pH	8.03±0.02	8.53±0.04	8.28±0.75
COD (mg/L)	1,920.00±98.38	1,173.67±92.38	480.00±13.64
TKN (mg/L)	318.26±15.00	84.53±15.96	52.49±7.21
NH_4^+-N (mg/L)	178.27±0.09	65.12±0.01	41.98±1.08
TDS (mg/L)	9,973.33±302.88	7,518.33±263.83	5,735.00±12.55
SS (mg/L)	826.44±9.20	260.00±23.09	223.00±8.05
VSS (mg/L)	491.67±7.07	212.22±13.47	104.00±11.32
BOD (mg/L)	285±15.23	56.00±7.26	12.00±3.72
BOD/SCOD	0.15	0.05	0.03

experimental design for each proportion. Mature leachate contains toxic and inhibitory compounds. At high concentrations, these substances inhibit microbial activity and reduce methane production. The addition of distilled water may dilute these inhibitors, allowing microorganisms to function more effectively. In experiment I, distilled water was used to provide a control and baseline condition (W100) for evaluating the effect of increasing leachate concentration. In experiment II, untreated leachate (mature leachate, ML) was mixed with treated leachate obtained through an adsorption process (TA) to investigate their combined effect as co-substrates and to optimize anaerobic digestion performance. This mixing strategy was intended to reflect a more practical and optimized approach to leachate utilization, in which partial treatment combined with mature leachate may provide a cost-effective and efficient solution for improving biogas production.

The batch experiment was performed using a 125 ml serum vial, with a working volume of 100 ml. According to the literature, the inoculum-to-substrate ratio (I/S) was maintained at 2 based on volatile solids (VS) (Muenmee and Prasertboonyai, 2021). The food waste and inoculum in required concentrations were added to the serum bottles; each digester was filled with varying ratios of leachate and distilled water to achieve a predetermined volume (100 ml) and solid content (10%). All serum bottles were purged with N_2 and sealed with rubber stoppers to maintain anaerobic conditions. All bottles were incubated at a stable mesophilic temperature of 35 ± 1 °C for 50 days to ensure completion of the methanogenic phase, accurate assessment of cumulative methane yield, and reliable evaluation of organic matter removal efficiency. The bottles were manually stirred bidaily throughout the experimental period. The biogas volume was quantified using the water displacement method. The gas composition was analyzed using a gas chromatograph (Bruker) fitted with a flame ionization detector. The injector, detector, and oven temperatures were 200 °C, 250 °C, and 150 °C, respectively. Helium functioned as the carrier gas at a flow rate of 1.0 mL/min. The experiments were triplicated, and the biogas production was reported.

Analytical methods

The analyzed leachate and digester parameters, encompassing pH, total solids (TS), volatile solids (VS), total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), alkalinity, and volatile fatty acids (VFA), were performed in accordance with standard methods for water and wastewater analysis (APHA, 2005).

RESULTS AND DISCUSSION

Characteristics of influent leachate samples

The leachate characteristics are reported in Table 2. It showed that the typical composition of a raw leachate had a relatively high level of COD (1,920.00±98.38 mg/L), total Kjeldahl nitrogen (TKN) (318.26±15.00 mg/L), and total dissolved solids (TDS) (9,973.33±302.88 mg/L), but they had a low BOD:COD ratio. The concentrations

Table 3. BMP experimental set-up

Experiment	Code	Leachate blend composition
I	W100	100% distilled water (W)
	W75:ML25	75% distilled water (W); 25% mature landfill leachate (ML)
	W50:ML50	50% distilled water (W); 50% mature landfill leachate (ML)
	W25:ML75	25% distilled water (W); 75% mature landfill leachate (ML)
	ML100	100% mature landfill leachate (ML)
II	ML75:TA25	75% mature landfill leachate (ML); 25% treated ML by adsorption (TA)
	ML50:TA50	50% mature landfill leachate (ML); 50% treated ML by adsorption (TA)
	ML25:TA75	25% mature landfill leachate (ML); 75% treated ML by adsorption (TA)
	TA100	100% treated ML by adsorption (TA)

of COD, TKN, TDS, VSS, and BOD of treated leachate by the stabilization pond were lower than those of raw leachate. As a result, treated leachate by the stabilization pond that was used in this study was considered as stabilized leachate or mature leachate due to the fact that the BOD:COD ratio was less than 0.1 and pH was also high (pH > 8). Although treated leachate by a stabilization pond was less polluted than the raw leachate, it did not meet the discharge standard because the mature leachate contained low biodegradable and nonbiodegradable compounds (Ferraz and Yuan, 2020; Ghahrchi and Rezaee, 2021). This result confirmed that biological treatment alone was not effective in stabilized leachate treatment. Considering characteristics of treated mature leachate by adsorption process (TA), the COD of TA was lower than the mature leachate. The COD and BOD removal efficiency of TA were 50.10% and 78.57%, respectively. Activated carbon is known as an effective adsorbent for organic matter (Ferraz and Yuan, 2020; Fazzino et al., 2021). However, the type of material used as the adsorbent is one of the important factors that relate to adsorption performance. Kaur et al. (2016) utilized cow dung-activated carbon for leachate treatment, achieving a 40% reduction in COD within the first hour and roughly 70% after 3 hours. Ferraz and Yuan (2020) investigated the removal of organic matter from landfill leachate via adsorption utilizing activated carbon derived from spent coffee grounds and reported that the activated carbon eliminated 80 ± 3% of COD and 90 ± 1.5% of color during a 3-hour monitoring period. Granular activated carbon (GAC) had the highest COD removal efficiency from leachate (100.0%), followed by washed sea sand (51.3%), zero-valent iron (42.0%), and dewatered alum sludge (16.0%) (Perera and Neetha Dayanthi, 2023). Besides organic pollutants, toxic metals contaminated in landfill leachate can be removed by the adsorption process. The adsorption efficiency of orange peel and banana peel adsorbent ranged from 99.90% to 99.99% for nickel, 59.30% to 82.91% for chromium, and 99.70% to 99.98% for cadmium in landfill leachate where the nickel, chromium, and cadmium concentrations were 9.6 mg/L, 4.90 mg/L, and 0.06 mg/L, respectively (Duwiejuah et al., 2024). Moreover, humic substances can interact with heavy metals found in leachate, creating positively charged complexes that adhere to the surface of activated carbons, hence enhancing the adsorption of organic matter (Ngoc et al., 2019).

Initial characteristics of the combination at various percentages of the treated leachate

The characteristics of feed at different ratios of treated leachate for experiments I and II are listed in Table 4. The feed parameters varied throughout the experiment due to changes in the types and amounts of leachate introduced. In experiment I, the content of TS, VS, and COD increased as the proportion of mature leachate increased, reflecting leachate composition. The leachate usually comprises suspended particles, heavy metals, and soluble organic and inorganic chemicals (Kurniawan et al., 2006; Ferraz and Yuan, 2020; Beinabaj et al., 2023). It should be noted that increasing the proportion of mature leachate resulted in a higher concentration of organic compounds in the batch reactors. Usually, the VFA concentration of mature leachate was low, and alkalinity was high, according to the low BOD/COD ratio and landfill age. Then, the VFA concentration range was 200.20–250.30 mg/L. The VFA concentration increased slightly, while the alkalinity increased visibly as the proportion of mature leachate increased. The VFA/alkalinity ratio is one of the most critical indicators for monitoring the stability of anaerobic digesters. The VFA/alkalinity ratio under 0.4 offers protection against failure from excessive acid build-up, in contrast to ratios above 1.0, where the decomposition tends to yield carbon dioxide and hydrogen as the primary gaseous products (Hernandez et al., 2014). The highest VFA/alkalinity ratio (0.71) was found at W100, followed by W75:ML25, W50:ML50, W25:ML75, and ML100, respectively. It indicated that the addition of mature leachate (ML) gave VFA/alkalinity ratio in the safe range for anaerobic digestion with less acidification risk (VFA/alkalinity ratio ≤0.4) (Hernandez et al., 2014). For the combination of ML and TA (in experiment II), the concentration of TS, VS, COD, VFA, pH, and alkalinity decreased as the proportion of TA increased according to the lower pollutant levels of TA compared to ML. The VFA/alkalinity ratios of all conditions were in the range of 0.35–0.42 and slightly increased with increasing the proportion of TA. This result indicated that increasing TA proportion could reduce pollutants (including organic matter) in the batch reactors.

Variation of pH

The variation of pH in the experiment I is shown in Figure 1. The pH value of the mature leachate (ML) is considered as alkaline as the pH is 8.53±0.04 (Table 1). As a result, the trend of pH at the beginning of the experiment I increased when the proportion of the ML increased. The pH values of W100, W75:ML25, W50:ML50, W25:ML75, and ML100 were 7.10±0.50, 7.17±0.70, 7.48±0.21, 7.77±0.24, and 8.02±0.54, respectively. The pH values of all batch reactors decreased within the first 10 days, and the lowest pH value was observed at W100 (the pH value was 5.26±0.21). A decrease in pH value was observed due to VFA production by acid-forming bacteria, which corresponded to an increase in VFA concentration. These results confirmed that hydrolysis and acidification occurred in the first 10 days. After that, the pH value of all batch reactors trended to increase, reaching a neutral level at 20 days except for W100, where the pH value was below 5. At W100, the pH value trend continuously decreased until 30 days; after that, it began to increase. During the preliminary phase of batch digestion, carbohydrates from organic waste were transformed into volatile fatty acids (VFAs), resulting in a reduction of liquid pH. Over time, the pH progressively rose as volatile fatty acids were transformed into biogas and proteins were decomposed into ammonia/ammonium (Syaichurrozi et al., 2026). Irreversible acidification may occur due to the accumulation of VFA generated from the hydrolysis of high organic content (Linyi et al., 2020). The buildup of VFA due to the lower pH value will have an impact on the production of biogas, which is produced by methanogen activity. Alkalinity serves as a quantification of an aqueous solution's ability to chemically buffer against changes in pH. Then, the anaerobic digester needs adequate alkalinity to provide sufficient buffering capacity to maintain the optimum pH range of 6.7 to 7.4 (Elazhar et al., 2022). The concentration and types of buffering compounds available are influenced by the overall organic load and the substrate itself.

Table 4. The characteristics of feed at different ratios of treated leachate

Experiment	Condition	Parameters						
		TS (mg/L)	VS (mg/L)	COD (mg/L)	pH	VFA (mg/L)	Alkalinity (mg/L)	VFA/ Alkalinity
I	W100	12,240.00±678.82	4,950.20±466.69	8,133.67±461.88	7.10±0.50	200.20±10.50	280.20±10.15	0.71
	W75:ML25	12,910.20±296.99	6,002.52±876.81	10,133.00±923.00	7.27±0.70	205.15±35.50	528.20±55.35	0.39
	W50:ML50	13,680.45±131.32	7,170.42±541.49	10,500.87±523.76	7.58±0.21	217.52±25.55	595.85±15.50	0.37
	W25:ML75	15,820.30±301.08	8,370.00±456.42	11,066.65±905.20	7.97±0.54	235.35±35.00	665.50±25.50	0.35
	ML100	17,180.22±187.94	8,670.65±636.40	11,733.33±150.00	8.32±0.50	250.30±15.20	770.55±52.00	0.32
II	ML75:TA25	16,460.00±169.71	8,460.42±868.81	13,866.67±968.76	8.25±0.32	240.50±10.50	680.00±14.14	0.35
	ML50:TA50	15,190.30±890.96	8,050.35±191.42	12,800.00±565.69	8.20±0.20	232.50±25.20	620.00±38.28	0.37
	ML25:TA75	14,770.70±523.26	7,125.40±343.50	12,066.37±433.50	8.19±0.31	225.50±52.00	580.10±28.80	0.39
	TA100	13,510.52±636.40	6,170.55±494.98	10,793.33±550.00	8.17±0.10	216.40±25.40	510.00±50.20	0.42

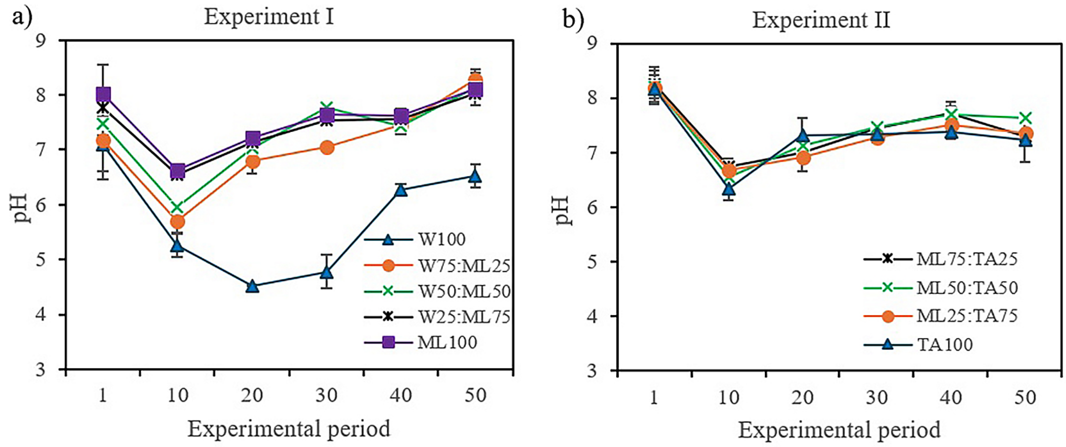

Figure 1. The variation of pH in different conditions; (a) Experiment I, (b) Experiment II

Initially, the alkalinity of all conditions ranged from 280.20 to 770.55 mg/L, and the trend of alkalinity increased when the proportion of the ML increased. Consequently, the drastic pH drop was detected at W100, where alkalinity was the lowest. The pH value of W75:ML25, W50:ML50, W25:ML75, and ML100 could return to normalcy within 20 days according to the appropriate VFA/alkalinity ratio. In contrast, the pH value of W100 couldn't return to normalcy until the end of the experiment.

In experiment II (for the combination of ML and TA), the pH value of all conditions in the experiment II ranged from 8.17 to 8.32. The trend of pH variation of all conditions during the experiment period in the experiment II was similar to the experiment I. The pH values of all conditions decreased within the first 10 days; after that, the pH values trended to increase, reaching a neutral level at 20 days. The pH value of all conditions remained stable due to the appropriate VFA/alkalinity ratio.

Methane generation

The cumulative methane yields from experiments I and II are shown in Figure 2 and Table S1. For the combination of distilled water (W) and mature leachate (ML), all conditions where the ML was added to the system showed an increase in methane production within 14 days, while W100 (100% distilled water) showed an increase in methane production within 32 days. Acidification by accumulating VFAs is one of the common inhibitors of biogas production and causes the lag phase (Siegert and Banks, 2005; Kim and Kim, 2020; Muenmee and Prasertboonyai, 2021; Syaichurrozi et al., 2026). The incorporation of ML into the system ensured sufficient buffering capacity to sustain the optimal pH by neutralizing the volatile fatty acids that may be generated inside the system. As a result, providing adequate buffering capacity to maintain the optimum pH by adding mature leachate could reduce the lag phase. The highest methane accumulation (148.79±10.00 mL/g_{vs}) was found at W75:ML25, while the lowest methane accumulation (53.66±11.20 mL/g_{vs}) was found at W100 (no mature leachate was added). The results of this study were consistent with research conducted by Nair et al. (2014); the system with 100% old leachate generated more biogas than the system with only organic waste. This result also confirmed the previous investigation; inhibition of biogas generation by VFA accumulation occurred without raw leachate addition (Xiaofeng et al., 2014). For the other ratios (W50:ML50, W25:ML75, and ML100), an increase in the proportion of ML led to a decrease in methane accumulation, even though the higher proportion of ML resulted in more biodegradable material (in terms of VS and COD) within the system.

In addition to having an adequate number of nutrients and biodegradable materials, leachate also contains dangerous substances like heavy metals (like iron, lead, and cadmium), salts (like chlorides), refractory organic compounds, and persistent xenobiotic chemicals. Previous research has reported that suitable concentrations of heavy metals may enhance microbial activity and consequently augment digestive efficiency, as some metals (e.g., Zn, Fe, and Mn) are essential for enzymes and coenzymes participating in biochemical processes (Gao et al., 2021). Nevertheless, excessive heavy metals induce cytotoxicity

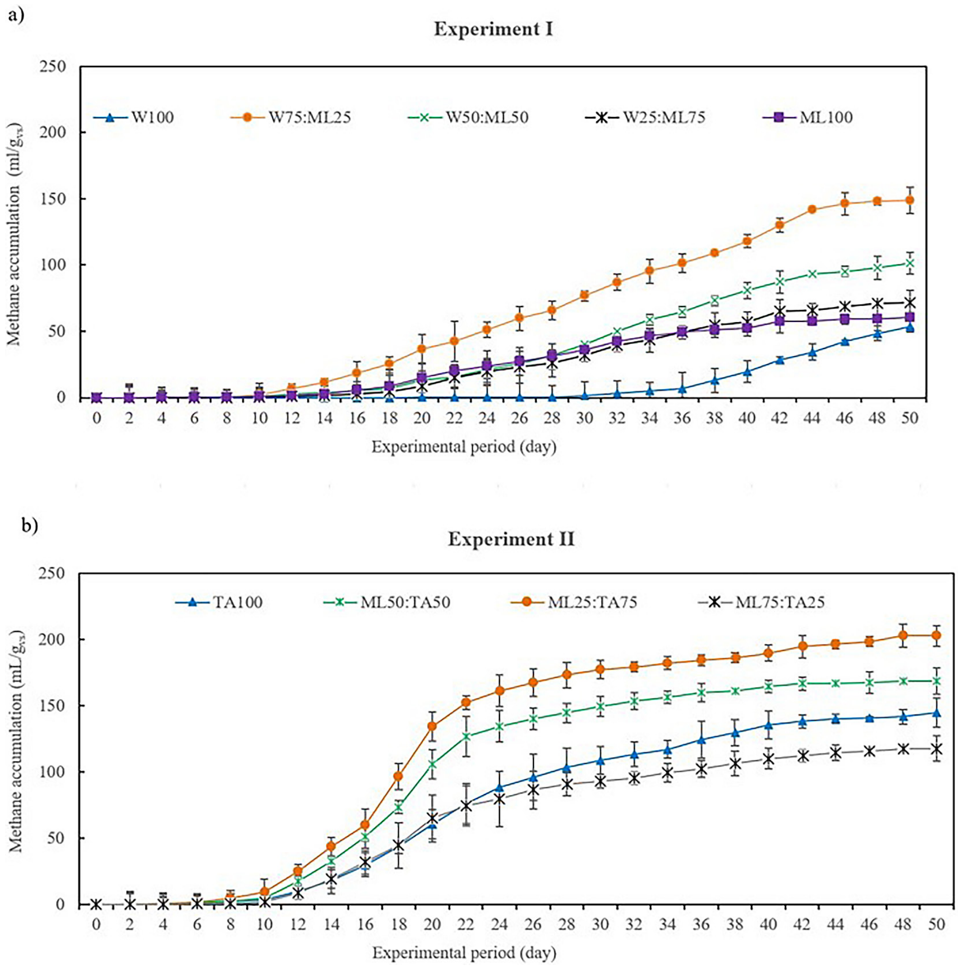

Figure 2. The methane accumulation in different conditions; (a) Experiment I, (b) Experiment II

and may result in the failure of the digestive system. Augmenting the ratio of mature leachate elevated the concentration of hazardous chemicals within the system. Consequently, the result achieved in the present study indicated that adding excessive mature leachate to the system could reduce methane accumulation according to mature leachate composition. This outcome aligned with the research conducted by Li et al. (2021), who examined the co-digestion of leachate and sludge, indicating that a mixing ratio of 5% to 15% was more advantageous for methane production than a ratio of 30%, and the overall biogas production from co-digestion was improved by 17.7–66.3%. Methane yield decreased to near zero when 100% leachate was supplied (Kawai et al., 2012).

In experiment II, all conditions showed an increase in methane production within 10 days and continued to rise steeply until around day 24, after that, the rate of accumulation slowed down. The lag phase, which was obtained in the experiment II, was shorter than the experiment I. Then, adding TA in the system could reduce the lag phase. The highest methane accumulation was found at ML25:TA75, followed by ML50:TA50, TA100, and ML75:TA25, respectively. For the combination of ML and TA conditions, increasing the TA proportion increased methane accumulation according to the lower pollutants of TA compared to ML. Activated carbon or biochar can remove substances like organic matter, heavy metals, and color from the leachate (Foo et al., 2013; Ferraz and Yuan, 2020; Aftab et al., 2024; Duwiejuah et al., 2024). Consequently, adsorption processes preferentially remove the toxic substances from the leachate. A similar result was obtained from Aftab et al. (2024), who studied the integration of adsorption processes with the membrane distillation for landfill leachate treatment and found that biochar could reduce foulant precursors and enhance membrane distillation performance. Besides toxic substances, methane generation also depends on the amount of biodegradable material provided. In experiment II, TA100 had the lowest organic matter in terms of COD and VS provided in the system. Then, a lower methane accumulation of TA100 than that of ML25:TA50 and ML50:TA50 were observed. These results emphasize that, although the primary substrate (co-substrate as organic waste and leachate) is similar across studies, the type of pre-treated leachate selection and mixing ratio affect methane production.

A common parameter for assessing the quality of biogas is methane concentration. Table 5 shows the maximum methane content in biogas under various conditions. The results of maximum methane content related to the methane accumulation. In experiment I, the maximum methane concentration of co-digestion of organic waste with ML was 30.14–52.51%, which was higher than anaerobic digestion of organic waste alone (29.25%). For co-digestion, the highest methane concentration was found at W75:ML25, followed by W50:ML50, W25:ML75, and ML100. These results indicated that the quality of biogas was improved by co-digestion of organic waste and mature leachate. However, an excess proportion of ML (more than 25%) could reduce the quality of biogas. The highest methane content obtained from the experiment II (55.00±3.52%) was a little higher compared to experiment I (52.51±4.62%). This result indicated that mature leachate pre-treated by the adsorption process could increase biogas quality due to reducing toxic substances in mature leachate. As a result, adding the appropriate volume of ML and TA in the system was essential for enhancing biogas quality, impacting both production volume and methane concentration, which dictates energy value.

Removal of organic matter

The efficacy of the anaerobic digestion process was evaluated by calculating the percentage reduction of VS and COD at the end of each BMP experiment, based on the initial and final VS and COD content for each condition. The final VS and COD concentrations are shown in Table S1. The percentage of reduction in organic matter after a 50-day digestion period in different conditions is shown in Figure 3. In the experiment I, the COD removal efficiency of W75:ML25 (82.11±9.45%) was the highest, followed by W50:ML50 (75.00±11.70%), W25:ML75 (67.50±6.50%), ML100 (59.36±10.45%), and W100 (55.71±9.60%), respectively. The COD removal of ML100 was a little higher than the results obtained from Nair et al. (2014), who studied the anaerobic digestion of organic fraction of municipal solid waste through leachate blending, found that the COD removal efficiency was 47% for proportion of 100% mature leachate. The trend of VS removal was similar to COD removal efficiency, and the trend of VS and COD removal efficiency was related to methane accumulation. COD and VS are eliminated by converting organic compounds into methane; hence, the methane generation potential of waste correlates with the quantity of organic matter present and the system's removal effectiveness. Low methane gas production and low COD and VS removal efficiency were observed where no mature leachate was added in the batch reactor, although mature leachate may contain toxic substances that can inhibit biogas production. The outcomes could be attributed to the reduced pH value in the system. These results implied that adding mature leachate in the system could enhance methane accumulation and organic matter removal efficiency, and the mixture with a 75% distilled water and 25% mature leachate ratio gave the highest methane accumulation and organic matter removal efficiency.

For the combination of ML and TA (experiment II), the highest VS and COD removal

Table 5. The maximum methane content under various conditions

Experiment	Condition	Maximum methane content (%)
I	W100	29.25±3.50
	W75:ML25	52.51±4.62
	W50:ML50	45.92±5.52
	W25:ML75	37.95±2.20
	ML100	30.14±3.40
II	ML75:TA25	39.20±4.20
	ML50:TA50	53.80±1.50
	ML25:TA75	55.00±3.52
	TA100	31.40±4.50

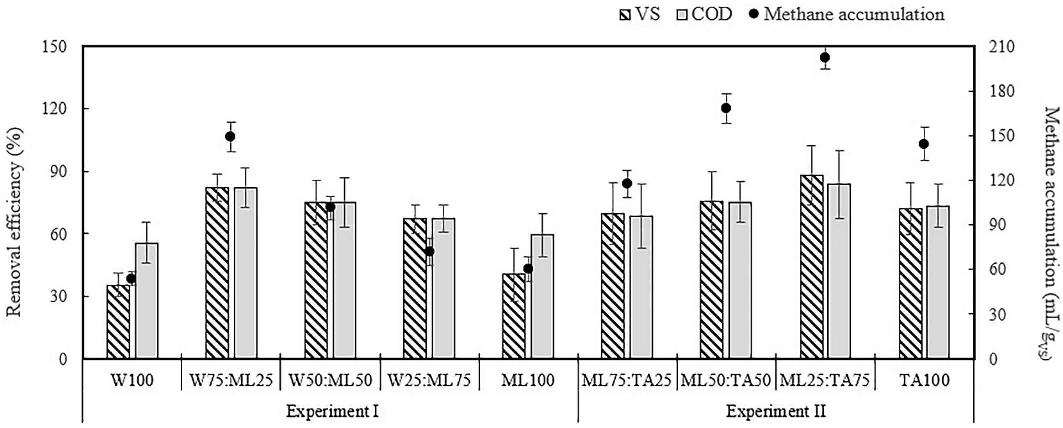

Figure 3. The organic removal efficiency and methane accumulation in different conditions

efficiency were found at ML25:TA75, followed by ML50:TA50, TA100, and ML75:TA25, respectively. The trend of VS and COD removal efficiency was related to methane accumulation. This result indicated that COD and VS removal efficiency and methane accumulation were higher when the optimum ML and treated leachate by adsorption (TA) proportion was provided.

For the mono-liquid type, treated leachate by adsorption (TA100) had the highest VS and COD removal efficiency and methane accumulation, followed by mature leachate (ML100) and distilled water (W100). This outcome indicated that the co-digestion of food waste with TA had higher methane production potential and organic removal efficiency than both the co-digestion of food waste with ML and the mono-digestion of food waste. For the combination of liquid types, the COD and VS removal efficiency of the mixture of ML and TA was higher than that of the mixture of W and ML. The results of COD and VS removal efficiency were related to methane accumulation; the highest accumulation of methane was observed in conditions with high COD and VS removal efficiency. The findings indicated that the combination of ML and TA could enhance organic removal efficiency and methane production in anaerobic digestion. The outcomes of the experiments I and II demonstrated that increasing the proportion of ML decreased methane accumulation and treatment performance, although increasing the proportion of ML increased organic matter in the system. The appropriate proportion of ML was 25% for both experiments I and II, and the methane accumulation of ML25:TA75 was higher than that of W75:ML25. The finding revealed that treated leachate by adsorption (TA) could be used instead of distilled water to enhance the methane production and treatment performance due to the organic matter and essential nutrients provided.

CONCLUSIONS

The results obtained in this study demonstrated that co-digestion of food waste with mature leachate provides better treatment performance and biogas production according to the buffering ability of the anaerobic digestion process. The addition of mature leachate at an optimal proportion (25%) improved buffering capacity, reduced lag phase, and increased methane yield compared to mono-digestion. However, excessive mature leachate (>25%) negatively affected performance due to the presence of inhibitory substances. Pretreated leachate by adsorption further improved system stability and digestion efficiency. The mixture of 25% mature leachate and 75% treated leachate by the adsorption process (ML25:TA75) demonstrated the highest methane accumulation and organic removal efficiency. This result confirmed that adsorption effectively reduced toxic compounds while retaining beneficial nutrients. Moreover, replacing distilled water with treated leachate by the adsorption process is a promising strategy to enhance anaerobic digestion performance, promote sustainable leachate management, and improve renewable energy recovery from organic waste.

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