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Anaerobic digestion of high salinity wastewater and methane production

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ABSTRACT

Anaerobic digestion of fish meal wastewater with high salinity and sodium (Na) content was investigated. The wastewater was collected from a fish meal factory. The chemical oxygen demand (COD) and pH of the wastewater were 8,530 mg/L and 6.58, respectively. The characteristics of wastewater were appropriate to be digested anaerobically except for the high salinity (13.03 ppt) and the Na content (7,986 mg/L). The wastewater was treated using single-stage and two-stage processing systems at room temperature (30°C). The organic loading rates to the single-stage reactors were 0.28, 0.43, 0.85 and 1.71 kg COD/m^3 d. The organic loading rates to the two-stage reactors were approximately five times higher than those of the single-stage reactors. The results revealed that the percentage of methane (CH_4) production from both types of operation was approximately 21%. For single-stage and two-stage operation, the COD degradation efficiency reached 75% and 69%, respectively; however, the maximum CH_4 yield was 45 and 36 L, respectively, at STP/kg COD degraded, at an organic loading rate of 0.28 and 1.42 kg COD/m^3 d, respectively. An anaerobic process can be used for the treatment of organic wastewater with high salinity and Na content but not for CH_4 production. The results indicated that high salinity and Na content adversely affected methane production.

Keywords: Anaerobic digestion; Biogas; Fish meal; Global warming; Greenhouse gas; Methane; Salinity; Sodium content; Two-stage digestion; Wastewater

1. Introduction

Global consumption of fish has increased in both developing and developed countries [1]. The projected total consumption of food fish per capita in 2020 for the developing and developed countries is estimated to be 16.2 and 21.5 kg/capita/year, respectively [2]. Water consumption in the fish-processing industry and the high strength of wastewater are of great concern. Canada, Sweden, China, India and Thailand are countries where the fishery sectors (catching and processing) contribute significantly to the national gross domestic product [1]. Fish-processing operations produce wastewater containing organic contaminants, including high contents of chemical oxygen demand (COD), nutrients, oil and fat. The level of COD varies largely between factory and fish type.

Thailand is now a leading fishing nation and as water consumption in fish processing is very large, pollution control in fish-processing plants in Thailand could be achieved through water conservation and water reuse [3]. Thailand is located in Southeast Asia, bordering the Andaman Sea of the Indian Ocean and the Gulf of Thailand in the South. Fish meal factories are important in Thailand where there are 23 coastal provinces and 96 fish meal processing factories, with 19 factories in the central part, 67 factories in the south and 10 factories in the east of the country [4]. The raw material used in fish meal includes small mackerel, sardines, anchovies and

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other small ocean fish types and additives such as sodium chloride (NaCl). Fish is a source of high quality protein that is easier to digest compared with other animal proteins. High-strength fish meal wastewater should be treated using good waste management and treatment technology.

Anaerobic technology is considered favorable for high-strength wastewater treatment. Anaerobic systems are well suited to the treatment of fish-processing wastewater because a high degree of biodegradable organic degradation can be achieved at a significantly lower cost than with comparable aerobic systems, resulting in the generation of only a small amount of sludge [5]. However, the differences in anaerobic treatment performance can be explained by the different wastewater characteristics, which include salinity [6]. High salinity in wastewater affects the performance of biological processes because high salinity could cause unbalanced osmotic stress across the cell wall and lead to plasmolysis as water is lost from microbial cells through osmosis [6]. This could eventually lead to the failure of biological treatment systems [7].

Anaerobic biodegradation is carried out by three groups of bacteria: (1) hydrolytic and fermentative bacteria, which hydrolyze the long-chain molecules to organic acids; (2) acetogenic bacteria, which convert these acids to acetate, hydrogen (H_2) and carbon dioxide (CO_2); and (3) methanogenic bacteria, which convert the end products of acetogenic reactions to methane (CH_4) and carbon dioxide (CO_2). Some studies have proposed the phase separation in two phases to improve CH_4 production [8–11]. The phase separation increases the stability of the process by preventing the build-up of toxic material [12]. The metabolic pathways of the two-stage anaerobic digestion process are the same as those of single-stage anaerobic digestion; they are physically separated into: (1) an acidogenic stage (hydrolytic and acetogenic stage) and (2) a methanogenic stage.

The work of Omil et al. [13,14] on fish-processing effluent using an anaerobic contact system showed that the adaptation of an active methanogenic biomass at the salinity level of the effluent was possible with a suitable strategy. Dimroth and Thomer [15] found that at low concentrations, Na is essential for methanogens. McCarty [16] reported Na concentrations in the range 100–200 mg/L to be beneficial for the growth of mesophilic anaerobes. According to Kugelman and Chin [17], the optimal Na content for mesophilic aceticlastic methanogens in waste treatment processes was 230 mg Na/L. The optimal growth conditions for mesophilic hydrogenotrophic methanogens reportedly occurred at 350 mg Na/L [18]. However, Lefebvre and Moletta [19] reported that methanogenesis was strongly inhibited by Na concentration of more than 10 g/L. At high concentrations, Na could readily affect the activity of microorganisms and interfere with their metabolism [20,21]. The level of inhibition depends on the concentration of Na. The IC50 for Na inhibition has been reported to be 5.6–53 g/L, depending on the adaptation period, antagonistic/synergistic effects, substrate and reactor configuration [7,13,14,18,20,22–29].

The current research investigated the biodegradation of organics in the fish meal wastewater and the production of biogas through an anaerobic process using a single-stage and a two-stage operation system. The two-stage processes had the aim to prevent the build-up of salt which is a toxic material to the microorganisms. The organic waste degradation efficiency and the CH_4 production in terms of CH_4 content and CH_4 yield were reported.

2. Methodology

2.1. Wastewater and mixed microorganisms

Fish meal wastewater was collected from a fish meal wastewater treatment plant in Samut Sakorn coastal province, near the Gulf of Thailand. Mixed microorganisms were collected from the wastewater treatment plant in order to acclimate the microorganisms to high concentrations of light metals (Na, K, Ca, Mg among others) over prolonged periods of time and to increase the tolerance and shorten the lag phase before CH_4 production began. The characteristics of the wastewater were analyzed for COD, total volatile solids (TVS), total solids (TS) and pH according to the procedures of standard methods [30]. The salinity and conductivity of the wastewater were measured using a portable salinity/conductivity meter (model WTW). Nitrogen (N) was determined using the Kjeldahl method by digesting samples to convert organic nitrogen to NH_4–N and determining NH_4–N in the digest [31]. Total phosphorous (P) was determined by digesting samples with sulfuric acid and analyzing using the ascorbic acid method [32]. Elemental analysis was performed by using an atomic absorption spectrometer (GBC, AVANTA, Australia); however, for Na and K, an emission technique was used. The experiments were performed based on the characteristics of normal fish meal wastewater.

In this study, normal starch wastewater was selected to compare its characteristics with the fish meal wastewater in terms of salinity. The salinity of normal starch wastewater was recorded.

2.2. Anaerobic single-stage operation

Four sets of reactors were constructed using plastic bottles. Each set consisted of a 6 L working volume which was equipped with two outlet ports, one for effluent and other for gas venting (Fig. 1). The reactor was connected to a gas collection system, which was based on water displacement by the exiting gases (using 0.05 M sulfuric acid to substitute water). Approximately 1 L of mixed microorganisms were added to each reactor and their concentrations were recorded in terms of mixed liquor volatile suspended solids (MLVSS). This reactor was operated by daily feeding with the wastewater semi-continuously in an upflow mode with wastewater at various flow rates of 200, 300, 600 or 1,200 mL/d resulting in hydraulic retention times (HRT) of 30, 20, 10 and 5 d, respectively.

The organic loading rates (OLRs) of the single-stage operation were 0.28, 0.43, 0.85 and 1.71 kg COD/m^3 d. The pH of wastewater was adjusted to approximately 7 using sodium bicarbonate ($NaHCO_3$) in the start-up period. During the operation, the reactors functioned without pH control. The operating period was 80 d.

2.3. Anaerobic two-stage operation

Five sets of reactor were constructed using plastic bottles. Each set consisted of two reactors (an acidogenic

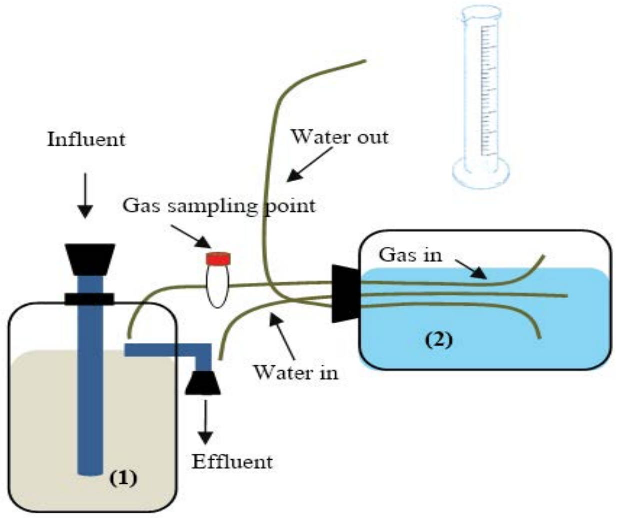

Fig. 1. Single-stage experimental set-up: (1) anaerobic reactor and (2) gas collection system.

and a methanogenic reactor), with working volumes of 1.5 and 4.5 L, respectively (Fig. 2). Total gas was corrected in the same manner as that of the single-stage operation. Mixed microorganisms were added to each acidogenic reactor and each methanogenic reactor for approximately 300 mL and 1 L, respectively and their concentrations were recorded in terms of MLVSS. Initially, the wastewater was added to the acidogenic reactor at a rate of 0.5 L/d for 3 d. The acidogenic reactor was equipped with two outlet ports, with one port for gas venting and the other for digested wastewater, both of which fed to the methanogenic reactor. The acidogenic reactor was fed with wastewater at various flow rates of 250, 500, 1,000, 1,500 and 2,000 mL/d giving rise to HRTs of 6, 3, 1.5, 1 and 0.75 d, respectively, in the acidogenic reactor and 18, 9, 4.5, 3, and 2.25 d, respectively, in the methanogenic reactor. The OLRs of the two-stage operation were 1.42, 2.84, 5.69, 8.53 and 11.37 kg COD/m^3 d. The pH of

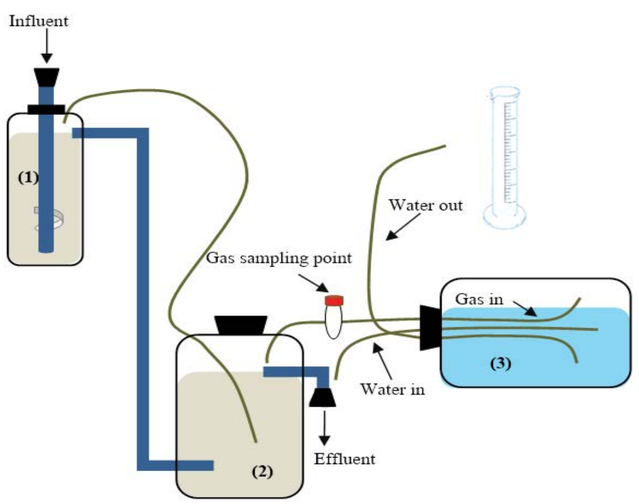

Fig. 2. Two-stage experimental set-up: (1) acidogenic reactor, (2) methanogenic reactor and (3) gas collection system.

the wastewater in the methanogenic reactor was adjusted to approximately 7 using sodium bicarbonate ($NaHCO_3$) in the start-up period. During the operation, the reactors functioned without pH control. The operating period was approximately 70 d.

For both types of operation, the results were recorded under steady-state conditions. The steady-state conditions indicate that there is stability in the reactors for the anaerobic reactions that produce biogas and COD in the effluent. The time to reach the steady state of each reactor was the time that exceeded its HRT. The ambient temperature of all reactors was 30°C. When the system reached steady state, the total gas production was recorded (at ambient temperature) daily and the CH_4 content was determined using a Shimadzu GC-14B (Japan) gas chromatograph equipped with a thermal conductivity detector (GC-TCD). The CH_4 volumes were then adjusted to standard temperature and pressure (STP). The digested wastewater from the methanogenic reactor was analyzed for COD, TVS, TS and pH according to the procedures of the standard methods [30]. All experiments were conducted in duplicate and the results were calculated using the mean of the experimental values. Organic waste degradation (in terms of %COD and %TVS degradation efficiency) and CH_4 production from the systems at various OLRs were used as indicators of reactor performance. The CH_4 yield was calculated and reported in terms of CH_4 produced/kg COD (and kg TVS) added to and degraded in the reactor.

3. Results and discussion

3.1. Characteristics of fish meal wastewater

The raw fish meal wastewater concentration used in the test was chemically analyzed because the most important parameters of biogas production are the composition of the waste. The analyses of the wastewater consisted of COD, TS, TVS, N (nitrogen), P (phosphorous), pH and trace elements. The COD of fish meal wastewater from the plant was 8,530 mg COD/L. These were characteristics of the wastewater generated during fish meal production and it was diluted with water from the overall process prior to disposal. TS and TVS were 9,720 and 6,370 mg/L, respectively. The N content was 204 mg/L and the P content was 1.24 mg/L. The pH was 6.58 (close to neutral). The salinity was 13.03 ppt. The characteristics of the wastewater are shown in Table 1.

Because of the high organic content and nearly neutral pH, the fish meal wastewater in the present study was ready for rapid degradation by microorganisms. N and P are needed in CH_4 production for their nutritious value. The COD:N was 100:2.39 which was suitable for anaerobic digestion. The recommended COD:N ratio of organic substrate is 100:2.5 in order to assimilate the microorganisms using anaerobic digestion [33]. The conductivity of the wastewater was 20.67 m Siemens/cm which showed that this fish meal wastewater had a high metals content (Table 1). Calcium (Ca), magnesium (Mg), iron (Fe) and copper (Cu) were low, while potassium (K) was moderate (Table 1). Only sodium (Na) was clearly high at 7,986 mg/L (Table 1). High Na was the main cause of the high salinity and conductivity in the wastewater.

Table 1
Characteristics of fish meal wastewater

Parameter	Value
Chemical oxygen demand (COD, mg/L)	8,530
Total solids (TS, mg/L)	9,720
Total volatile solids (TVS, mg/L)	6,370
pH	6.58
Salinity (ppt)	13.03
Conductivity (mS/cm)	20.67
Nitrogen (TKN, mg/L as N)	204
Phosphorous (PO_4^{3-}, mg/L as P)	1.24
K (mg/L)	104
Na (mg/L)	7,986
Ca (mg/L)	0.26
Mg (mg/L)	0.43
Fe (mg/L)	2.73
Cu (mg/L)	0.03
COD:N	100:2.39
COD:N:P	100:2.39:0.015
COD:P	200:0.038

From the characteristics of the fish meal wastewater, only the salinity (caused by Na) was different from other types of food wastewater. The salinity of the fish meal wastewater was clearly higher than in other normal types of organic wastewater. For comparison, the salinity of starch wastewater was measured and recorded at 1.08 ppt. The fish meal wastewater was rich in organic matter, protein-based N, and a large amount of salt (NaCl) which is required for fish conservation.

Chowdhury et al. [1] reported that fish processing is characterized by COD values of 1,000–18,000 mg/L and an N content of 80–1,000 mg/L. Normally, the pH of wastewater from a fish-processing factory was in the range 5.7–7.4 with an average pH of 6.48 [34]. The TS of fisheries are generally 2,000–3,000 mg/L; however, with tuna processing it can be much higher at 17,900 mg/L [34].

3.2. Reactor performance of single-stage operation

The bacterial cell concentration was 14,400 mg MLVSS/L and the COD of the fish meal wastewater fed into the reactor was 8,530 mg COD/L, yielding a bacterial cell:COD of 1.69 g cell/g COD. The 6 L working volume reactors were fed at flow rates of 200, 300, 600 and 1,200 mL/d, which resulted in HRTs of 30, 20, 10 and 5 d, respectively, which corresponded to OLRs of 0.28, 0.43, 0.85 and 1.71 kg COD/m^3 d, respectively.

3.2.1. Methane production from single-stage operation

Under steady-state conditions, the total gas produced from the reactors of the different OLRs of 0.28, 0.43, 0.85 and 1.71 kg COD/m^3 d was 267, 340, 600 and 866 mL at STP/d, respectively. The average CH_4 content was 21.34%, 21.15%, 18.16% and 14.89% which varied inversely to OLR. Thus, the CH_4 production obtained by calculation was 57, 72, 109 and 129 mL at STP/d. All results are summarized in Table 2. Normally, the average CH_4 content obtained from anaerobic digestion of food wastewater should be 60% or more [35]. In this study, the highest CH_4 content from anaerobic digestion of the fish meal wastewater was only 21.34% which was obtained from the OLR of 0.28 COD/m^3 d (HRT 30 d) fed to the reactor. The fish meal wastewater had the characteristics of normal food wastewater, except the salinity of the fish meal wastewater was much higher. The salinity of fish meal wastewater was approximately 13 times higher than that of the normal starch wastewater (the salinity of normal starch wastewater was recorded at 1.08 ppt). This might show the inhibitory effect of salinity on methanogenesis stage. The result in this study was good in concurrence with a previous work which revealed that Na concentrations ranging from 3,500 to 5,500 mg/L were moderately and 8,000 mg/L were strongly inhibitory to methanogens at mesophilic temperatures [16].

3.2.2. Organic waste degradation from single-stage operation

At the steady-state condition, the average pH of the effluent in all reactors was neutral (Table 2). The effluent

Table 2
Reactor performance from fish meal wastewater anaerobic digestion using single-stage operation at various OLRs and HRTs

Parameters	Organic loading rate, kg COD/m^3 d			
	0.28	0.43	0.85	1.71
Reactor volume (mL) for each anaerobic reactor	6,000	6,000	6,000	6,000
Flow rate (mL/d)	200	300	600	1,200
HRT (d) in the anaerobic reactor	30	20	10	5
Initial MLVSS (mg/L)	14,400	14,400	14,400	14,400
Initial pH	6.58	6.58	6.58	6.58
Average pH at steady state	7.39	7.28	7.11	6.89
Initial COD (mg/L)	8,530	8,530	8,530	8,530
COD at steady state (mg/L)	2,129	3,000	4,215	5,189
COD degradation efficiency (%)	75.04	64.83	50.59	39.17
Initial TVS (mg/L)	6,370	6,370	6,370	6,370
TVS at steady state (mg/L)	1,520	1,890	2,598	3,276
TVS degradation efficiency (%)	76.14	70.30	59.21	48.57
Initial TS (mg/L)	9,720	9,720	9,720	9,720
TS at steady state (mg/L)	2,797	3,590	4,946	5,918
TS degradation efficiency (%)	71.22	63.05	49.10	39.10
Total gas production (mL at STP/d)	267	340	600	866
Average CH_4 (%)	21.34	21.15	18.16	14.89
CH_4 production (mL at STP/d)	57	72	109	129
CH_4 yield (L at STP/kg COD added)	33	28	21	13
CH_4 yield (L at STP/kg COD degraded)	45	43	42	32
CH_4 yield (L at STP/kg TVS added)	45	38	28	17
CH_4 yield (L at STP/kg TVS degraded)	59	54	48	35

obtained from OLRs of 0.28, 0.43, 0.85 and 1.71 kg COD/m³ d contained 2,129, 3,000, 4,215 and 5,189 mg COD/L, respectively (or 1,520, 1,890, 2,598 and 3,276 mg TVS/L, respectively). The highest COD degradation of 75.04% (or TVS degradation of 76.14%) was obtained for anaerobic digestion of the fish meal wastewater at the minimum OLR of 0.28 kg COD/m³ d and the maximum HRT of 30 d (Table 2). Increasing OLR from 0.28 kg COD/m³ d to 1.71 kg COD/m³ d, the COD and TVS degradation efficiency obviously dropped. The result is concurrent with that from the previous study. Prasertsan et al. [36] conducted anaerobic filter process in treating fishery wastewater and tuna condensate and found that the highest COD degradation of 84% was obtained for fishery wastewater at an OLR of 0.3 kg COD/m³ d and HRT of 36 d and the data from their study showed that with an increase in OLR, the COD degradation efficiency dropped.

The negative effects of salinity on anaerobic digestion of treatment efficiency of fish meal wastewater have been reported. Although the organic degradation efficiency in terms of COD and TVS was up to 75% and 76% at an OLR of 0.28 kg COD/m³ d (Table 2), the CH_4 content was low for all OLRs of the study. The highest CH_4 content was only 21.34%. This might show the inhibitory effect of salinity on methanogenesis stage.

3.2.3. Methane yield from single-stage operation

The CH_4 yield at different OLRs was calculated in terms of liters of CH_4 produced/kg COD (or TVS) added to the reactor and liters of CH_4 produced/kg COD (or TVS) degraded in the reactor. CH_4 yield = V/QS_0, where V is the CH_4 produced in the reactor, Q is the flow rate and S_0 is the organic strength of the substrate in terms of COD or TVS added to the reactor. CH_4 yield = $V/Q(S_0 - S)$, where S is the effluent COD or TVS obtained from the reactor, thus, $(S_0 - S)$ is the organic substrate degraded in the reactor. The results are summarized in Table 2 and Figs. 3(a)–(d). The maximum CH_4 yields of just 33 L/kg COD added (or 45 L/kg TVS added) and 45 L/kg COD degraded (or 59 L/kg TVS degraded) were obtained at an OLR of 0.28 kg COD/m³ d

3.3. Reactor performance of two-stage operation

The bacterial cell concentration in the acidogenic and methanogenic reactor was 7,200 and 14,400 mg MLVSS/L, respectively, and the COD of the wastewater was 8,530 mg COD/L yielding a bacterial cell:COD in the acidogenic and methanogenic reactor was 0.84 and 1.68 g cell/g COD. The 1.5 L working volume acidogenic reactors were fed at the

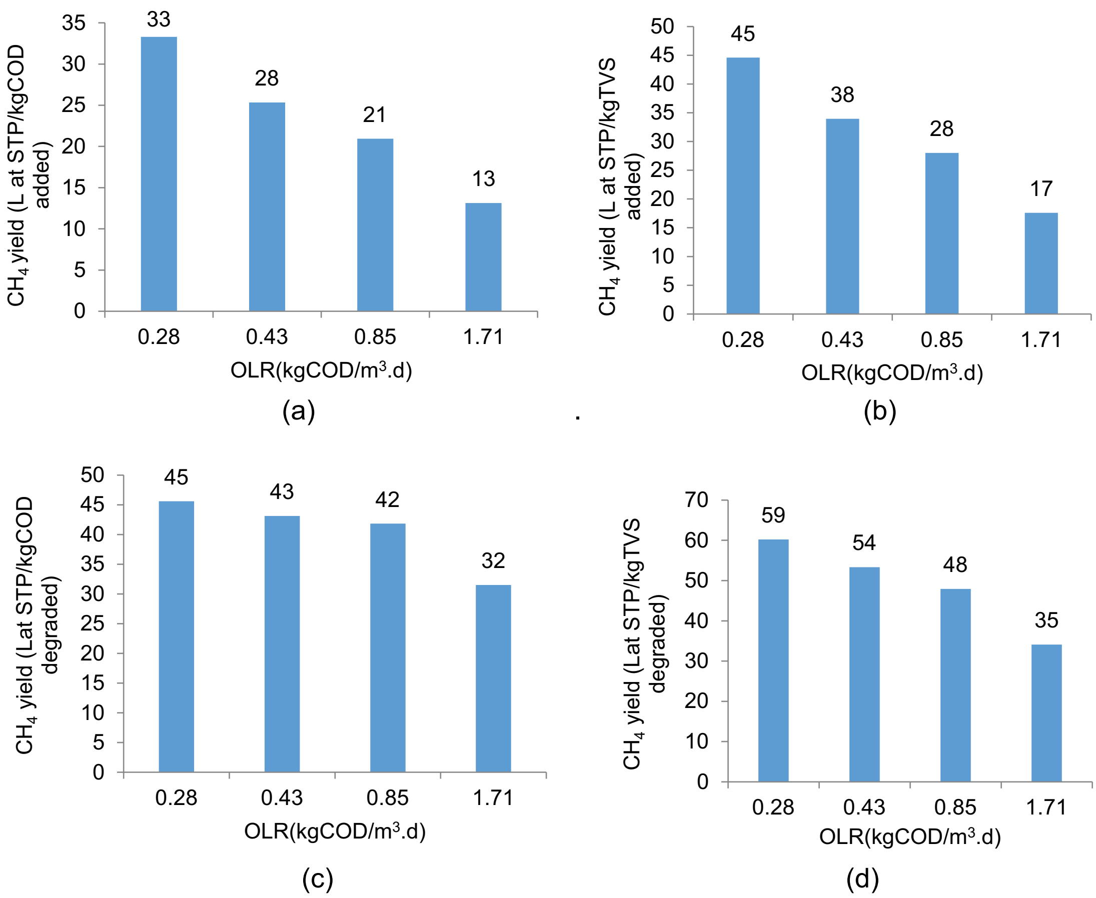

Fig. 3. CH_4 yield obtained from anaerobic digestion of fish meal wastewater at various OLRs using single-stage operation in terms of: (a) kg COD added to the reactor, (b) kg TVS added to the reactor, (c) kg COD degraded in the reactor and (d) kg TVS degraded in the reactor.

flow rates of fish meal wastewater of 250, 500, 1000, 1,500 and 2,000 mL/d, thus, resulted in HRTs in acidogenic reactors of 6, 3, 1.5, 1 and 0.75 d which corresponded to the OLRs of 1.42, 2.84, 5.69, 8.53 and 11.37 kg COD/m^3 d, respectively (Table 3). The HRTs of the wastewater in each 4.5 L methanogenic reactor were 18, 9, 4.5, 3 and 2.25 d, respectively (Table 3).

3.3.1. Methane production from two-stage operation

At the steady-state condition, the total gas produced from the reactors of various OLRs of 1.42, 2.84, 5.69, 8.53 and 11.37 kg COD/m^3 d was 255, 331, 497, 597 and 748 mL at STP/d, respectively (Table 3). The average CH_4 content was 20.80%, 18.76%, 15.50%, 15.42% and 13.63% (Table 3) and varied inversely with the OLR. Thus, the CH_4 production obtained by calculation was 53, 62, 77, 92 and 102 mL/d at STP, respectively (Table 3). Although the operation type was changed to two-stage anaerobic digestion, the CH_4 content produced was comparable with that from the single-stage operation and CH_4 production was not satisfactorily high. The results are summarized in Table 3. The highest CH_4 content from anaerobic digestion using the two-stage operation was only 20.80% which was obtained from an OLR of 1.42 kg COD/m^3 d.

3.3.2. Organic waste degradation from two-stage operation

Under the steady-state conditions, phase separation was achieved. The average pH of the effluent in the acidogenic reactors was acidic and the pH of methanogenic reactors was neutral (Table 3). The effluent obtained from OLRs of 1.42, 2.84, 5.69, 8.53 and 11.37 kg COD/m^3 d contained 2,616, 3,508, 4,198, 4,387 and 5,652 mg COD/L, respectively (or 1,290, 2,053, 3,028, 3,134 and 4,100 mg TVS/L, respectively). The highest COD reduction of 69.33% (or TVS 79.75%) was obtained for anaerobic digestion of the fish meal wastewater at the minimum OLR of 1.42 kg COD/m^3 d and the maximum HRT of 6 and 18 d in the acidogenic reactor and methanogenic reactor, respectively (Table 3). Increasing the OLR to the acidogenic reactor from 1.42 to 11.37 kg COD/m^3 d resulted in reduced COD and TVS efficiency (Table 3).

3.3.3. Methane yield from two-stage operation

The CH_4 yield at different OLRs using the two-stage operation was calculated in terms of liters of CH_4 produced/kg COD (or TVS) added to the reactor and liters of CH_4 produced/kg COD (or TVS) degraded in the reactor in the same manner as those for the single-state operation.

Table 3
Reactor performance from fish meal wastewater anaerobic digestion using two-stage operation at various OLRs and HRTs

Parameter	Organic loading rate (kg COD/m^3 d)				
	1.42	2.84	5.69	8.53	11.37
Reactor volume (mL) for each acidogenic, methanogenic reactor	1,500, 4,500	1,500, 4,500	1,500, 4,500	1,500, 4,500	1,500, 4,500
Flow rate (mL/d)	250	500	1,000	1,500	2,000
HRT (d) for each acidogenic, methanogenic reactor	6, 18	3, 9	1.5, 4.5	1, 3	0.75, 2.25
Initial MLVSS (mg/L) in acidogenic and methanogenic reactor	7,200, 14,400	7,200, 14,400	7,200, 14,400	7,200, 14,400	7,200, 14,400
Initial pH	6.58	6.58	6.58	6.58	6.58
Average pH of acidogenic reactor at steady state	6.18	6.09	5.97	5.93	5.86
Average pH of methanogenic reactor at steady state	7.32	7.11	6.98	6.96	6.86
Initial COD (mg/L)	8,530	8,530	8,530	8,530	8,530
COD at steady state (mg/L)	2,616	3,508	4,198	4,387	5,652
COD degradation efficiency (%)	69.33	58.87	50.78	48.57	33.74
Initial TVS (mg/L)	6,370	6,370	6,370	6,370	6,370
TVS at steady state (mg/L)	1,290	2,053	3,028	3,134	4,100
TVS degradation efficiency (%)	79.75	67.77	52.46	50.80	35.64
Initial TS (mg/L)	9,720	9,720	9,720	9,720	9,720
TS at steady state (mg/L)	2,906	3,472	4,368	4,684	6,076
TS degradation efficiency (%)	70.10	64.27	55.04	51.80	37.47
Total gas production (mL at STP/d)	255	331	497	597	748
Average CH_4 (%)	20.80	18.76	15.50	15.42	13.63
CH_4 production (mL at STP/d)	53	62	77	92	102
CH_4 yield (L at STP/kg COD added)	25	14	9	7	6
CH_4 yield (L at STP/kg COD degraded)	36	25	18	15	17
CH_4 yield (L at STP/kg TVS added)	33	19	12	10	8
CH_4 yield (L at STP/kg TVS degraded)	42	29	23	19	22

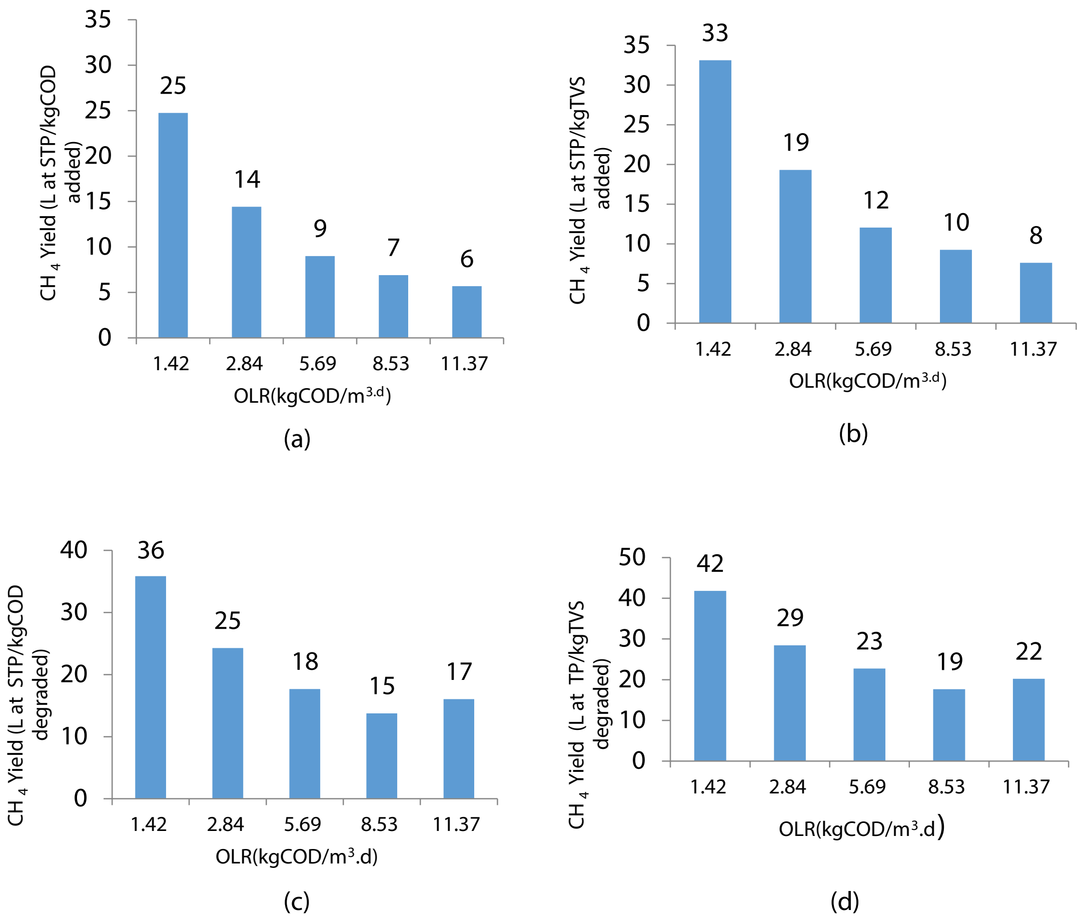

Fig. 4. CH_4 yield obtained from anaerobic digestion of fish meal wastewater at various OLRs using two-stage operation in terms of: (a) kg COD added, (b) kg TVS added to the reactors, (c) kg COD degraded and (d) kg TVS degraded in the reactors.

The results are summarized in Table 3 and Figs. 4(a)–(d). The maximum CH_4 yields of just 25 L/kg COD added (or 33 L/kg TVS added) and 36 L/kg COD degraded (or 42 L/kg TVS degraded) were obtained at an OLR of 1.42 kg COD/m^3 d (Table 3).

4. Discussion

The single-stage and two-stage operation of anaerobic treatment could achieve high organic degradation for some OLRs (Tables 2 and 3) but the CH_4 production and the CH_4 yields were very low (Tables 2 and 3; Figs. 3 and 4). This led to the conclusion that the anaerobic process could reduce the organics in the fish meal wastewater and implied that the organics were not satisfactorily transformed to CH_4. Thus, the anaerobic process was suitable for organic degradation in fish meal wastewater but the process was not suitable for CH_4 production. The salinity of 13.03 ppt and the associated Na content of 7,986 mg/L might not inhibit microorganisms in the organic biodegradation of fish meal wastewater but might strongly inhibited methanogens in CH_4 production. The CH_4 yields obtained were much lower than the theoretical CH_4 yield of 350 L at STP/kg COD degraded [37]. Although the anaerobic process could reduce organics in the fish meal wastewater, the produced biogas contained a low CH_4 content.

OLRs have a great influence on the biodegradation of organic matter in the wastewater, reflected by the COD and TVS degradation efficiency and the biogas yield. Although the OLRs for the two-stage anaerobic reactor in this study were approximately five times higher than those of single-stage reactors, the COD and TVS degradation efficiency of both systems were comparable. This showed that the two-stage operation achieved better biodegradation efficiency than the single stage. The only disadvantage of the two-stage process was that it required more sophisticated equipment and process control, resulting in the operation being more expensive.

5. Conclusion

Anaerobic digestion of fish meal wastewater with a high salinity level achieved high organic degradation for some OLRs but the CH_4 production and the CH_4 yield were not acceptably high. Single-stage anaerobic digestion achieved 75% of COD degradation efficiency at an OLR of 0.28 kg COD/m^3 d but the CH_4 yield was just 45 L at STP/kg COD degraded. Two-stage anaerobic digestion achieved 69%of COD degradation efficiency but the maximum CH_4 yield was just 36 L at STP/kg COD degraded at an OLR 1.42 kg COD/m^3 d. Two-stage operation could carry a higher OLR. The CH_4 content obtained from anaerobic digestion by both types of operation was approximately 21%. Two-stage anaerobic digestion could not prevent toxicity of the methanogens due to the high salinity. Thus, the high salinity of the fish meal wastewater negatively affected the process of CH_4 production but not for organic waste digestion. This showed that salinity adversely affected methanogenesis. The anaerobic process can be used for the treatment of organic wastewater with high salinity and Na content but not for the purpose of CH_4 production.

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References

[1] P. Chowdhury, T. Viraraghavan, A. Srinivasan, Biological treatment processes for fish processing wastewater – a review, Bioresour. Technol., 101 (2010) 439–449.

[2] C.L. Delgado, N. Wada, M.W. Rosegrant, S. Meijer, M. Ahmed, The Future of Fish: Issues and Trends to 2020 (Issue Brief), International Food Policy Research Institute (Washington, DC) and the World Fish Center, Penang, Malaysia, 2003.

[3] M. Achour, O. Khelifi, I. Bouazizi, M. Hamdi, Design of an integrated bioprocess for the treatment of tuna processing liquid effluents, Process Biochem., 35 (2000) 1013–1017.

[4] Office of Agricultural Economics, Bureau of Agricultural Economics Research, Ministry of Agriculture and Cooperatives, Agricultural Economics Research 113, March 2012 (in Thai) http://www.oae.go.th.

[5] M.R. Johns, Developments in wastewater treatment in the meat processing industry: a review, Bioresour. Technol., 54 (1995) 203–216.

[6] X. Shi, O. Lefebvre, K.K. Ng, H.Y. Ng, Sequential anaerobic–aerobic treatment of pharmaceutical wastewater with high salinity, Bioresour. Technol., 153 (2014) 79–86.

[7] M.V.G. Vallero, L.W. Hulshoff Pol, G. Lettinga, P.N.L. Lens, Effect of NaCl on thermophilic (55°C) methanol degradation in sulfate reducing granular sludge reactors, Water Res., 37 (2003) 2269–2280.

[8] B. Demirel, O. Yenigün, Two-phase anaerobic digestion processes: a review, J. Chem. Technol. Biotechnol., 10 (2002) 743–755.

[9] B. Kasapgil Ince, O. Ince, Changes to bacterial community make-up in a two-phase anaerobic digestion system, J. Chem. Technol. Biotechnol., 75 (2000) 500–508.

[10] D.M. O'Keefe, D.P. Chynoweth, Influence of phase separation, leachate recycle and aeration on treatment of municipal solid waste in simulated landfill cells, Bioresour. Technol., 72 (2000) 55–66.

[11] H. Yu, Z. Samani, A. Hanson, G. Smith, Energy recovery from grass using two-phase anaerobic digestion, Waste Manage., 22 (2002) 1–5.

[12] N. Sinbuathong, P. Sirirote, B. Sillapacharoenkul, J. Munakata-Marr, S. Chulalaksananukul, Biogas production from two-stage anaerobic digestion of *Jatropha curcas* seed cake, Energy Sources Part A, 34 (2012) 2048–2056.

[13] F. Omil, R.J. Méndez, J.M. Lema, Characterization of biomass from a pilot plant digester treating saline wastewater, J. Chem. Technol. Biotechnol., 63 (1995) 384–392.

[14] F. Omil, R. Méndez, J.M. Lema, Anaerobic treatment of saline wastewaters under high sulphide and ammonia content, Bioresour. Technol., 54 (1995) 269–278.

[15] P. Dimroth, A. Thomer, A primary respiratory Na^+ pump of an anaerobic bacterium: the Na^+-dependent NADH:quinone oxidoreductase of Klebsiella pneumonia, Arch. Microbiol., 151 (1989) 439–444.

[16] P.L. McCarty, Anaerobic waste treatment fundamentals, Public Works, 95 (1964) 107–112.

[17] I.J. Kugelman, K.K. Chin, Toxicity, Synergism, and Antagonism in Anaerobic Waste Treatment Processes, In: Anaerobic Biological Treatment Processes, Chapter 5, American Chemical Society Advances in Chemistry Series 105, New Brunswick, N.J., 1971, pp. 55–90.

[18] G.B. Patel, L.A. Roth, Effect of sodium chloride on growth and methane production of methanogens, Can. J. Microbiol., 23 (1977) 893–897.

[19] O. Lefebvre, R. Moletta, Treatment of organic pollution in industrial saline wastewater: a literature review, Water Res., 40 (2006) 3671–3682.

[20] A. Rinzema, J. van Lier, G. Lettinga, Sodium inhibition of acetoclastic methanogens in granular sludge from a UASB reactor, Enzyme Microb. Technol., 10 (1988) 24–32.

[21] R. Gourdon, C. Comel, P. Vermande, J. Veron, Kinetics of acetate, propionate and butyrate removal in the treatment of a semi-synthetic landfill leachate on anaerobic filter, Biotechnol. Bioeng., 33 (1989) 1167–1181.

[22] Y. Liu, D.R. Boone, Effects of salinity on methanogenic decomposition, Bioresour. Technol., 35 (1991) 271–273.

[23] M. Soto, R. Méndez, J.M. Lema, Sodium inhibition and sulphate reduction in the anaerobic treatment of mussel processing wastewaters, J. Chem. Technol. Biotechnol., 58 (1993) 1–7.

[24] G. Feijoo, M. Soto, R. Méndez, J.M. Lema, Sodium inhibition in the anaerobic digestion process: antagonism and adaptation phenomena, Enzyme Microb. Technol., 17 (1995) 180–188.

[25] E. Aspé, M. Marti, M. Roeckel, Anaerobic treatment of fishery wastewater using a marine sediment inoculum, Water Res., 31 (1997) 2147–2160.

[26] I.S. Kim, D.H. Kim, S.H. Hyun, Effect of particle size and sodium ion concentration on anaerobic thermophilic food waste digestion, Water Sci. Technol., 41 (2000) 67–73.

[27] M.V. Vallero, L.W. Hulshoff Pol, P.N. Lens, G. Lettinga, Effect of high salinity on the fate of methanol during the start-up of thermophilic (55°C) sulfate reducing reactors, Water Sci. Technol., 45 (2002) 121–126.

[28] W.H. Chen, S.K. Han, S. Sung, Sodium inhibition of thermophilic methanogens, J. Environ. Eng., 129 (2003) 506–512.

[29] M.V.G. Vallero, G. Lettinga, P.N.L. Lens, Long-term adaptation of methanol-fed thermophilic (55°C) sulfate-reducing reactors to NaCl, J. Ind. Microbiol. Biotechnol., 30 (2003) 375–382.

[30] APHA and AWWA, Standard Methods for the Examination of Water and Wastewater, 21st Ed., American Public Health Administration, Washington DC, 2005.

[31] A. Walkley, A critical examination of a rapid method for determination organic carbon in soils—effect of variations in digestions conditions and of inorganic soil constituents, Soil Sci., 63 (1947) 251–264.

[32] G.E. Rayment, F.R. Higginson, Australian Laboratory Handbook of Soil and Water Chemical Methods, Inkata Press, Melbourne/Sydney, Australia, 1992.

[33] G.K. Anderson, P. Sallis, S. Uyanik, Anaerobic Treatment Processes, D. Mara, N.J. Horan Jr. Eds., Handbook of Water and Wastewater Microbiology, Academic, London, UK, 2003, pp. 391–426.

[34] Technical Report Series FREMP WQWM-93-10, DOE FRAP 1993-39, Wastewater Characterization of Fish Processing Plant Effluents, Fraser River Estuary Management Program, New West Minister, BC, Canada, 1994.

[35] J. Kuo, J. Dow, Biogas production from anaerobic digestion of food waste and relevant air quality implications, J. Air Waste Manage. Assoc., 67 (2017) 1000–1011.

[36] P. Prasertsan, S. Jung, K.A. Buckle, Anaerobic filter treatment of fishery wastewater, World J. Microbiol. Biotechnol., 10 (1994) 11–13.

[37] G. Tchobanoglous, F.L. Burton, Wastewater Engineering: Treatment, Disposal, and Reuse, Revised from Metcalf & Eddy Inc., 3rd Ed., McGraw Hill Inc., Singapore, 1991.