

## Effect of Microwave and Ultrasonic Pretreatments on Biogas Production from Anaerobic Digestion of Palm Oil Mill Effluent

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**Abstract: Problem Statement:** Oil palm production is a major agricultural industry in Malaysia. In 2006, palm oil mills in Malaysia produced more than 58 million tonnes of Palm Oil Mill Effluent (POME). Existing treatment in a series of open lagoons at high ambient temperatures, results in the uncontrolled production of methane and carbon dioxide, which are both green house gases (GHGs). With the increased worldwide concern on environmentally friendly production processes particularly the emission of methane, it is important to develop an alternative concept for POME treatment. This study elucidates the effects of pre-treatment of palm oil mill effluent by microwave irradiation and ultrasonic on anaerobic digestion. **Approach:** Effects of pre-treatment on sludge characterisation parameters were monitored. The Soluble Chemical Oxygen Demand (SCOD)/total COD ratio and biodegradability of soluble organic matter increased significantly after both the pre-treatments which indicated an increase in disintegration of the floc structure of the sludge. Three identical bioreactors with working volume of 5 litres were used as anaerobic digesters at 32-35°C. The reactors were separately fed with pre-treated sludge (microwave, ultrasonic and combination of microwave and ultrasonic) and control sludge at different Hydraulic Retention Times (HRT) to check for the production of methane. **Results:** The maximum SCOD/TCOD ratio reached almost 29% after 30 min of ultrasonic treatment, while it was 45% after 7 min of microwave irradiation. The BOD<sub>5</sub>/SCOD ratio also increased after the pre-treatments suggesting the biodegradability of the soluble organic material increased during the treatment. It was observed that TVFA released was increased after both the treatments, with microwave treatment showing a higher yield of TVFA. Greatest enhancement in methane production was shown by the 3 min microwave plus 10 min ultrasonic treatment. **Conclusion:** The microwave in combination with ultrasonic would be a rapid and economical method for sludge pre-treatment for enhancement of biogas production.

**Key words:** Anaerobic digestion, microwave pretreatment, ultrasonic pre-treatment, methane, Palm Oil Mill Effluent (POME)

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### INTRODUCTION

Many branches of agriculture and food industries such as dairy, edible oil, fat refining, slaughterhouse, wool scouring and meat processing plants have a considerable wastewater output. The problem of pollution is not caused only by the total amount of wastewater production, but also by the content of organic matter. The bioprocesses that will be used to treat wastewater in the future will be focused on the need to exploit resources rather than only pollution control. Many bioprocesses can provide bioenergy or valuable chemicals while simultaneously achieving the objective of pollution control. Industrial wastewaters,

for example, from food-processing industries and breweries and agricultural wastewaters from animal confinements are ideal candidates for bioprocessing because they contain high levels of easily degradable organic material, which results in a net positive energy or economic balance, even when heating of the liquid is required. Such wastewaters are potential commodities from which bioenergy and biochemicals may be produced. Recovery of energy and valuable materials might reduce the cost of wastewater treatment and some what reduce our dependence on fossil fuels<sup>[1]</sup>. Anaerobic digestion is a natural process in which bacteria convert organic materials into biogas. Biogas can be collected and used as a potential energy resource.

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Table 1: Characteristics of raw POME<sup>[4]</sup> and the regulatory discharge limits<sup>[14]</sup>

Parameter	Value (All values, except pH and temperature, (all values, except pH expressed in mg/L.)	Regulatory discharge limit (All values, except pH and temperature, are expressed in mg/L.)
Temperature (°C)	80-90	45
pH	4.7	5.0-9.0
Biochemical Oxygen Demand (BOD <sub>3</sub> , 3 days at 30°C <sup>(a)</sup> )	25,000	100 (50) <sup>(b)</sup>
Chemical Oxygen Demand (COD)	50,000	-
Total Solids (TS)	40,000	-
Total Suspended Solids (TSS)	18,000	400
Total Volatile Solids (TVS)	34,000	-
Oil And Grease (O&G)	4,000	50
Ammonia-Nitrogen (NH <sub>3</sub> -N)	35	150 <sup>(c)</sup>
Total Kjeldahl Nitrogen (TKN)	750	200 <sup>(c)</sup>

(a) Statutory incubation conditions. (b) This additional limit is the arithmetic mean value determined on the basis of a minimum of four samples taken at least once a week for four weeks consecutively. (c) Value of filtered sample.

Oil palm production is a major agricultural industry in Malaysia. In 2006, there were more than 4.2 million hectares of oil palm plantations which produced 16 million tonnes of oil<sup>[2]</sup>. In total, about 110 million tonnes of renewable non-oil biomass (trunk, fronds, shells, palm press fiber and the empty fruit bunches) are produced each year. Furthermore approximately 0.65 tonnes of raw palm oil mill effluent (POME) is produced for every ton of fresh fruit bunches. In 2006, palm oil mills in Malaysia produced more than 58 million tonnes of POME<sup>[2]</sup>. POME is an acidic brownish colloidal suspension characterized by high contents of organics and solids and is discharged at a temperature of 80-90°C (Table 1). It has been estimated that POME contributes to about 30% of the total biochemical oxygen demand (BOD) load exerted on the Malaysian aquatic environment. Wastewater treatment facility is one of the most important components in the palm oil industry. This facility is normally used to treat a large volume of POME generated during the production of Crude Palm Oil (CPO) before the effluent is safely discharged to the surrounding environment through water canal or river. Specifically, the amount of POME generated is approximately 3.8 m<sup>3</sup> for each ton of CPO produced<sup>[3]</sup>. The problems associated with aerobic treatment of POME using a pond system are long retention time (90-120 days), large area requirement, high demand for maintenance, loss of nutrition and high emission of methane. Since methane is a greenhouse gas which is 21 times stronger than carbon dioxide, open ponds result in significant emissions of greenhouse gases. Existing treatment in a series of open lagoons at high ambient temperatures, results in the uncontrolled production of methane and carbon dioxide, which are both Green House Gases (GHGs). With the increased worldwide concern on environmentally friendly production processes

particularly the emission of methane, it is important to develop an alternative concept for POME treatment<sup>[4]</sup>. Anaerobic digestion is considered to be an effective treatment process for POME. If the POME is treated in an anaerobic digesting plant instead, the methane produced will be available for energy purposes. There have been growing interests in recovering biogas/methane from POME treatment as a clean renewable gaseous fuel for steam, power generation or other applications. Based on the gross annual CPO production of Malaysia of 14 million tonnes for 2004, the estimations made have shown a potential total methane recovery of 524,000 tones. With increasing demand for energy and cost effective environmental protection, anaerobic digestion biotechnology has become the focus of worldwide attention<sup>[5]</sup>. Moreover, it offers a positive environmental impact since it combines waste stabilization with net fuel production.

An anaerobic degradation of particulate organics is considered to be a sequence of three steps: hydrolysis, acidogenesis and methanogenesis. Among these, biological hydrolysis of the particulate organics has been considered to be a rate limiting step<sup>[6]</sup>. Because the sludge particles consist mainly of a polymeric network formed by extracellular polymeric substances and microbial cells that are resistant to direct anaerobic degradation since cell walls and extracellular polymeric substances present physical and chemical barriers<sup>[7]</sup>. It is widely documented that pre-treatment methods such as<sup>[8-13]</sup>, cause the lyses or degradation of sludge cells and particulates, the organic matter therefore becoming more accessible to anaerobic microorganisms. The efficiency of pre-treatment is commonly evaluated in terms of biodegradability or biogas production.

The next two stages in an anaerobic digestion are acidogenesis and methanogenesis. During the acid phase, bacteria convert complex organic compounds

(carbohydrates, fats and proteins) to simple organic compounds, mainly short-chain volatile organic acids (acetic, propionic and lactic acids). Subsequently, several species of strictly anaerobic bacteria (methanogenic microorganisms) called "methane formers" convert the acetate, hydrogen and carbon dioxide into methane gas (CH<sub>4</sub>). This process is referred to as methanogenesis. During this phase, waste stabilization occurs, represented by the formation of methane gas.

The aim of the present study was to examine the effects of acidic, microwave (an electromagnetic radiation with an oscillation frequency of 0.3-300 GHz.) and ultrasound pre-treatments as a cost effective and rapid technique for the sludge pre-treatment for enhancement of anaerobic digestion of POME. The alternating electric field by microwave irradiation causes a rapid alignment and realignment of dipoles in a polar solvent. Continuous repetition of alignment and realignment generates friction, thus resulting in heat generation<sup>[15]</sup>. Tsai<sup>[16]</sup> also reported that microwave method for cell lyses was fast and had many potential applications. Ultrasonic technology is a safe, clean and effective method to cause degradation of organics or cell lyses<sup>[17-19]</sup>. Therefore ultrasound can be used and integrated with other pre-treatment method for enhancement of anaerobic digestion. Because of the high energy demands of the processes, their energy balances were also examined.

## MATERIALS AND METHODS

The waste water from the palm oil mill known as Palm Oil Mill Effluent (POME) was obtained from Seri Ulu Langat Palm Oil Mill Sdn. Bhd., in Dengkil, Selangor. The fresh POME collected from the mill was brought to the lab and was stored at 4°C in tightly closed plastic containers until used.

**Pre-Treatments:** Total Volatile Solid (TVS) of the POME was determined as standard method Clescerl *et al.*<sup>[20]</sup> Well-mixed samples were filtered through a pre-weighed GF/C fibreglass filter and the residue retained on the filter was dried overnight to a constant weight in a 105 °C oven. The increase in weight of the filter represented the Total Solids (TS) portion. The dried filter was ignited at 550 °C in a muffle furnace for 20 min. The difference between ash and dry weights represented the fixed fraction of the sample and the difference between the TS and the fixed fraction was considered to be the TVS portion. The typical value for TVS for POME was around 32-34 g L<sup>-1</sup>. For all experiments the TVS of the POME was adjusted to around 2% (dilution with distilled) for the subsequent

experiments. The initial temperature of sludge was maintained at 10°C. The applied pre-treatments were performed separately to each sample of POME prior to batch experiments.

A microwave oven (2450 MHz, 700W) was used to irradiate the sludge. A series of experiments were performed at different irradiation times of 0 (control), 3, 5, 7, 9, 11 and 15 min to evaluate the degree of disintegration of organics in the sludge. Lab-scale ultrasonic treatments were applied to sample of POME at 10°C. In this setup, sample in batches of 200 mL each were sonicated using Cole-Parmer 130-Watt Ultrasonic processor (transducer: lead zirconate titanate piezoelectric). The frequency was 18 kHz and power input was adjusted between 0 to 100 W. Different ultrasonic intensity (0.20, 0.30 and 0.50 W mL<sup>-1</sup>) and sonication time (1, 5, 10 and 30 min) were applied. The transducer was mounted on a retort stand and the probe was lowered into the sludge. The beaker containing the sludge was placed on a magnetic stirrer. For combined ultrasonic and microwave pre-treatment, the samples were sonicated as mentioned above using 0.20W mL<sup>-1</sup> intensity for 10 and 30 min. After which each samples were subjected to microwave irradiation (2450 MHz, 700 W) for 3 and 7 min.

After the pre-treatment process Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) and Total Volatile Fatty Acids (TVFA) were measured using standard methods<sup>[20]</sup>. Biogas production tests were performed in batch mode under mesophilic conditions, at 30 °C in an anaerobic digester

**Batch Anaerobic digestion:** The experiments were performed using three well - mixed digesters. The digesters were mainly modified spinner flasks (Corning Proculture). The spinner flasks were of 10 L capacity and had a wide mouth (120 mm) and two angled arms (45 mm), which serve as liquid and gas sampling ports. Volumes of POME used were 5 L and the pH was maintained at 7.2. Temperature was maintained at 32-37°C using the hot plate and were well mixed using the magnetic bar stirrer. Hydraulic retention time (HRT) of 15,12,10,8,4 and 2 days were sequentially tried to investigate the performance of the anaerobic digestion of the pre-treated POME. There were total of 3 pre-treated sample; the microwave treated (3 min), the ultrasonic treated (10 min) and combination of both treatment (3 min microwave+10 min ultrasonic). A control reaction was performed using untreated POME. To obtained anaerobic condition, oxygen was removed by purging the headspace of the bottles with nitrogen gas for five min, after which the bottles mouth were capped tightly. The biogas was collected via the side arm (gas sampling port) which was connected to the graduated glass cylinder. Biogas production (volume)

was measured by using water displacement method of acidified water (pH 2-3) and its methane content by KOH solution displacement in a serum bottle, as described previously<sup>[21]</sup>.

### RESULTS

Table 2 summarizes the effect of microwave irradiation on sludge disintegration. The ratio of SCOD to TCOD increased as microwave irradiation time increased. This indicated that various cytoplasmic materials of the sludge were released into the medium as a result of cell wall disintegration. The samples began to over boil after 7 min of microwave irradiation and this duration was used in other studies.

The variations of SCOD/TCOD ratio under different ultrasonic treatments were studied. Fig. 1 and 2 represent separately the effects on SCOD/TCOD ratio under different ultrasonic intensity and sonication time respectively. Judging from these results, the most important parameter is sonication time. The ultrasonic intensity could barely influence the SCOD/TCOD ratio, this phenomena is coincident with other observations in this study. The maximum ratio of SCOD/TCOD reached about 0.32 after 30 min treatment, (using intensity of 0.5 W mL<sup>-1</sup>) while the ratio was about 0.29 after 30 min treatment (using intensity of 0.20 W mL<sup>-1</sup>). Hence, for the purpose of saving energy, the lowest power density (0.20 W mL<sup>-1</sup>) was sufficient and was employed throughout.

The use of pre-treatments especially microwaves and ultrasonic is a promising method for sludge disintegration, because of the rapid internal heating. A further strategy was to study the combined effects of both ultrasonic/microwave pre-treatments. Ultrasonic pre-treatment (using 0.20 W mL<sup>-1</sup>) for 10 and 30 min followed by a 3 and 7 min of microwave irradiation (2450 MHz and 700W) showed increase in the ratios of SCOD/TCOD and BOD<sub>5</sub>/SCOD as shown in Fig. 3 and 4. It was found that the combined ultrasonic/microwave pre-treatment increased the SCOD/TCOD ratio denoting that the release of organic materials from solid state to liquid (soluble), while BOD<sub>5</sub>/SCOD ratio also increased suggesting the biodegradability of the soluble

Table 2: Effect of microwave irradiation on sludge disintegration

Microwave irradiation time (min)	Microwave irradiation energy (kJ/l)	Final temperature (°C)	SCOD/TCOD	BOD <sub>5</sub> /SCOD
0	0	10.0	0.11	0.44
3	252	59.4	0.21	0.56
5	420	78.1	0.29	0.78
7	588	91.8	0.45	0.93
9	756	boiled	0.69	0.95
11	924	boiled	0.77	0.95

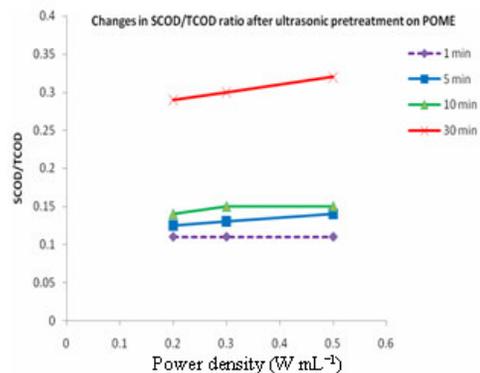


Fig. 1: Effect of ultrasonic pre-treatment on the SCOD/TCOD ratio at four different length of sonication time each with three different sonication intensity

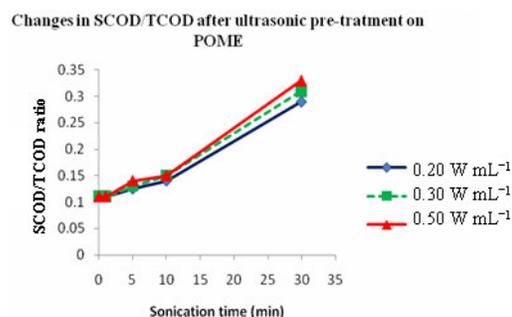
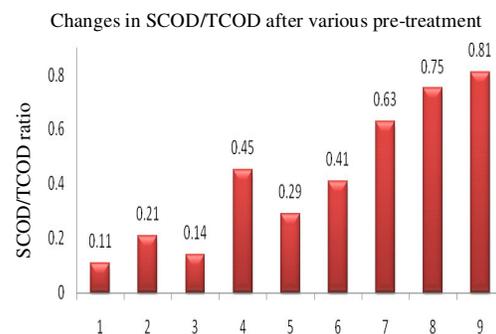


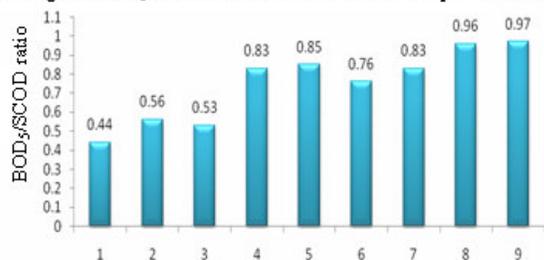
Fig. 2: The same data on effect of ultrasonic pre-treatment on the SCOD/TCOD ratio as in Fig. 1 but plotted against sonication time.



1. Control
2. Microwave irradiation- 3 min
3. Ultrasonic treatment- 10 min
4. Microwave irradiation- 7 min
5. Ultrasonic treatment- 30 min
6. Microwave irradiation-3 min & ultrasonic treatment 10 min.
7. Microwave irradiation-3 min & ultrasonic treatment 30 min.
8. Microwave irradiation-7 min & ultrasonic treatment 10 min.
9. Microwave irradiation-7 min & ultrasonic treatment 30 min.

Fig. 3: Effects of combined pre-treatments of ultrasound and microwave on the ratio of SCOD/TCOD

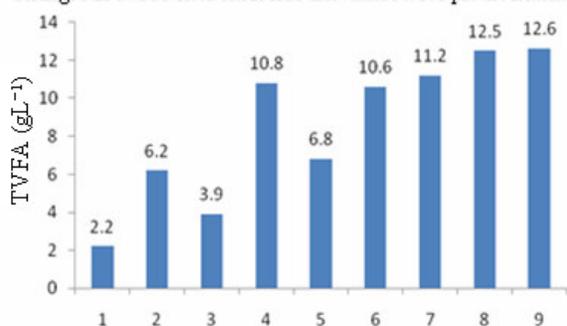
Changes in BOD<sub>5</sub>/SCOD after microwave ultrasonic pre-treatment



1. Control
2. Microwave irradiation- 3 min
3. Ultrasonic treatment- 10 min
4. Microwave irradiation- 7 min
5. Ultrasonic treatment- 30 min
6. Microwave irradiation-3 min & ultrasonic treatment 10 min.
7. Microwave irradiation-3 min & ultrasonic treatment 30 min.
8. Microwave irradiation-7 min & ultrasonic treatment 10 min.
9. Microwave irradiation-7 min & ultrasonic treatment 30 min.

Fig. 4: Effects of combined pre-treatments of ultrasound and microwave on the ratio of BOD<sub>5</sub>/SCOD

Changes in TVFA after ultrasonic and microwave pre-treatment



1. Control
2. Microwave irradiation- 3 min
3. Ultrasonic treatment- 10 min
4. Microwave irradiation- 7 min
5. Ultrasonic treatment- 30 min
6. Microwave irradiation-3 min & ultrasonic treatment 10 min.
7. Microwave irradiation-3 min & ultrasonic treatment 30 min.
8. Microwave irradiation-7 min & ultrasonic treatment 10 min.
9. Microwave irradiation-7 min & ultrasonic treatment 30 min.

Fig. 5: Effects of combined pre-treatments of ultrasound and microwave on the Total Volatile Fatty Acid (TVFA) produced

organic materials increased during the treatment. As shown in Fig. 4, there was significant difference between the effects produced by the combined ultrasonic treatment for 10 min or 30 min followed by microwave irradiation for 7 min as compared with the effects produced individually by 30 min ultrasonic or 7 min microwave irradiation. The highest increase was

Rate of Methane gas production after microwave and ultrasonic pre-treatment

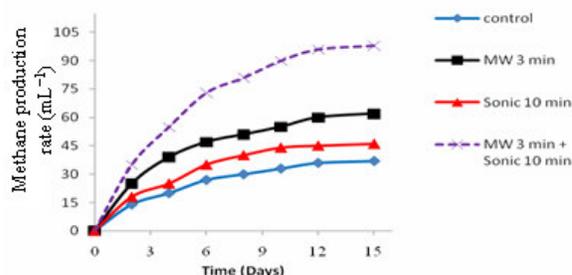


Fig. 6: The difference in methane production between the various pre-treated and control samples. (MW- denotes microwave treatment and Sonic-means ultrasonic treatment)

obtained by 10 min ultrasonic followed by 7 min microwave treatment.

Figure 5 depicts variations in total volatile fatty acids (TVFA) after ultrasonic and microwave treatment under different exposure times. The TVFA release is becoming obvious with the increase of sonication and microwave exposure time. It is observed that the microwave treatment shows a higher yield of TVFA as compared to ultrasonic treatment.

The use of pre-treatments especially microwaves and ultrasonic is a promising method for sludge disintegration, because of the rapid internal heating. The cell walls of both dead and living microorganisms in sludge are destroyed and the organic substances are digested due to the

The biogas production rate as a function of operational time at the given hydraulic retention times (HRT) is shown in Fig. 6. The biogas production was measured according to the method described previously<sup>[21]</sup>. The untreated sludge was used as control sample. The results in Fig. 6 revealed that all types of pre-treatment enhanced the methane production relative to the control (max 40 mL<sup>-1</sup> after 15 days).

The energy requirement for the pre-treatment processes can be assessed by estimating the amounts energy per unit mass of the sludge required to achieve a certain volume of methane (vol. of methane produced per litre sludge after 15 days). Table 3 shows the comparison of energy requirement for sludge disintegration using microwave and ultrasonic pre-treatment using data from the Fig. 6.

In the ultrasonic pre-treatment, approximately 44 mL of methane was produced after 10 min of treatment, which was equivalent to energy consumption of 120 kJ per litre sludge. This accounted to 19% increase in

Table 3: Comparison of microwave (MW) and ultrasonic (Sonic) pre-treatment for methane production

	Control	Microwave (2,450 MHz, 700 W)	Ultrasonic (20 kHz, 100 W)	Microwave plus Ultrasonic (2,450 MHz, 700 W +, 20 kHz 100 W))
POME volume	500 mL	500 mL	500 mL	500 mL
Treatment time	0	3 min	10 min	3 min (MW) + 10 min (Sonic)
Specific energy (KJ/L-sludge)	0	252	120	372
Methane Produced per litre sludge after 15 days	37 mL	58 mL	44 mL	98 mL

methane production over the control. However, 58 mL of methane (56.7% higher than control) was produced from 1 L of sludge after 3 min of microwave irradiation with energy consumption of 252 kJ per litre sludge. By using the assumption that the enhancement effect is linearly proportional with the duration of treatment, then we can assume that for 360 kJ (3 x 120) of energy input using ultrasonic treatment, the methane production would be about 57% higher than the control.

## DISCUSSION

The physico-chemical parameters of POME used in this study were typically the same as reported in Table 1<sup>[4]</sup>. Most palm oil mills in Malaysia have similar operations and the wastewater discharged is quite typical as seen in previous reports<sup>[22, 23]</sup>. Since the COD/BOD ratio of POME is about 1.8-2.0 a good possibility exists that the organic matter is biodegradable<sup>[24]</sup>. The main recalcitrant organic material found in POME as mentioned previously is lignocelluloses<sup>[25]</sup>. There is also a significant amount of oil and grease, which can be hydrolyzed by microorganisms to fatty acids. Some of these fatty acids are potential substrates for methane production which does allow a favourable economic outcome<sup>[26]</sup>. In contrast, there have been reports that lipid-rich waste contains long chain fatty acids, especially palmitate (higher than 50 mg G<sup>-1</sup> dry weight) and oleate (higher than 200 mg L<sup>-1</sup>), that were hydrolysis products of fat & oil, can inhibit bacterial growth and hence methane formation<sup>[27]</sup>. The high amounts of TS and TSS in the POME comes from insoluble organic substances being washed out during the production process.

Soluble COD (SCOD) displays the organic matter only in the liquid portion of the sludge while total COD (TCOD) reflects the organic matter in both the solid and liquid state of the sludge. TCOD should be stable

for the same sludge sample. Then, the increase of SCOD/TCOD ratio denotes the release of the organic materials from solid state to liquid state after pre-treatment treatment. With the increase of sonication time, there is an increase in the disintegration of floc structure, hence the rise of SCOD/TCOD ratio caused by the release of extracellular polymeric substances (EPS), which consists of polysaccharides, proteins and other macromolecule embedded in the floc matrix<sup>[28]</sup>. Further increase could also be contributed by the release of soluble organics from the disrupted cells.

Pre-treatments especially microwaves and ultrasonic is a promising method for sludge disintegration, because of the rapid internal heating. The cell walls of both dead and living microorganisms in sludge are destroyed and the organic substances are digested due to the heat effect. Volatile fatty acids (VFA) are fatty acids with a carbon chain of six carbons or fewer. Volatile fatty acids are very important part of the organic substances, which is easily absorbed by microorganisms, hence would be very important for the methane production during anaerobic digestion. As noted earlier (Table 2) the BOD<sub>5</sub>/SCOD ratio of the original POME was around 0.44. The ratio increased quickly with the microwave pre-treatment as shown in Table 2. Similarly the BOD<sub>5</sub>/SCOD ratio increase quickly with the sonication time. Using intensity of 0.20 W/mL and 10 min of sonication time, the ratio was 0.66. After 30 min of sonication (0.20 W mL<sup>-1</sup>) the ratio was 0.91. Hence biodegradability of organic matters was improved drastically by both microwave irradiation and ultrasonic pre-treatments.

The combined effects of both ultrasonic/microwave pre-treatment was also studied. As shown in Fig. 4, the highest increase in BOD<sub>5</sub>/SCOD was obtained by 10 min ultrasonic followed by 7 min microwave treatment. It is noteworthy that any further increase in time of the pre-treatments for the combined method did not show any significant improvement on the biodegradability. From Fig. 5, it can be observed that ultrasound will help to release the extracellular polymeric substances which among others consist of short chain organic matters embedded in the floc matrix due to effective disintegration of the floc structure<sup>[28]</sup>. Larger molecules and longer chain fatty acids may require further treatment to break into volatile fatty acid. Microwave treatment produces higher TVFAs because the rapid internal heating destroys the cell walls of both living and dead microorganism in the sludge and the organic compounds are digested due to heat effect. During longer exposure to microwave heating some of the long

fatty acid chains will also be broken down to short fatty acid chain. This will be beneficial because long chain fatty acids especially palmitate and oleate can inhibit bacterial growth and hence methane formation<sup>[27]</sup>. It is also interesting to note that the effects of both pre-treatments are not cumulative, as can be seen from the microwave treatment at 7 min plus ultrasonic treatment at either 10 min or 30 min which gave about the same amount of TVFA.

From Fig. 6, it shows that there is a slight difference in the methane production between combined microwave 3 min/ ultrasonic 10 min treatment (57% higher as compared to control) compared to only the 3 min microwave treatment (43% higher as compared to control). However the 7 min microwave plus 10 min ultrasonic treatment had the greatest enhancement, increasing the methane production by slight more than 103% as compared to control. It could be suggested that organics inside the cells were released as a result of cell lyses by microwave irradiation, thereby increasing their biodegradability over the control sludge. Therefore, pre-treated sludge became more susceptible for microbial attack primarily by acidogens than control sludge, thus providing better substrate for methanogens and enhancing the overall methane production rate. Sludge decomposition by microwave/ultrasound pre-treatment could be divided into three phases based on the conversion of organic matter: floc structure disintegrating and particle size decrease phase, cell breakage and macromolecular compounds release phase and conversion of macromolecular compounds to Volatile Fatty Acids (VFAs) phase.

Studying the data in Table 3 which shows the comparison of energy requirement for sludge disintegration using microwave and ultrasonic pre-treatment, we can see that by comparing similar amounts of methane produced, microwave pre-treatment required lesser energy input as compared to with ultrasonic treatment (42.8% lesser). In the combined treatment (microwave 3 min + ultrasonic 10 min), about 98 mL of methane was produced per litre sludge. This accounts for about 164 % more methane compared to the control. The energy input for this combined treatment process was calculated to be 372 kJ/L-sludge. By the same assumption, if we were to achieve similar enhancement using ultrasonic alone, we need to multiply by factor of 8.6 (19% x 8.6 = 163.4%), then the energy input would be estimated to be 1032 kJ/L-sludge. Again ultrasonic treatment alone is inefficient in terms of energy required. Finally by looking at microwave irradiation alone, as the method of pre-treatment, to obtain about 164% enhancement, we need to multiply by factor of 2.9 (56.7% x 2.9 = 164%), then

the energy input would be estimated to be 730.8 kJ/L-sludge.

## CONCLUSION

It could be concluded that the microwave in combination with ultrasonic would be a rapid and economical method for sludge pre-treatment for enhancement of biogas production. However, microwave irradiation alone would require double the energy required by the combined method. Nevertheless this higher energy requirement can be offset if we look at the capital cost required to install both the systems. Hence, in terms of instrumentation cost, process design and maintenance, microwave treatment alone would also be a viable option.

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