Effect of microwaves on solubilization of organic fraction of municipal solid waste

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ABSTRACT
High temperature and pressure microwave (MW) irradiation was investigated as a pretreatment for the organic fraction of municipal solid waste (OFMSW) in order to enhance solubilization before anaerobic digestion (AD). MW pretreatment resulted in higher soluble chemical oxygen demand (sCOD), proteins and sugars in the supernatant phase. At 175ºC, MW pretreatment resulted in 1.61±0.05 higher sCOD compared to control. Additionally for the same condition, the free liquid volume from bound water released from OFMSW into the supernatant was 1.39±0.01 times higher than the control. Concomitantly the increase in potentially bio-available sCOD increased significantly to more than 200% after microwaving at high temperature.

RÉSUMÉ
L'irradiation de micro-ondes (MO) à haute température et pression a été étudiée comme pré-traitement de la fraction organique des résidus solides municipaux (FORSM) pour améliorer leur solubilité avant la digestion anaérobique (DA). Les MO ont causé une hausse des concentrations de demande chimique en oxygène soluble (DCOs), de protéines et de sucres dans la phase surnageante. À 175ºC, la DCOs et le volume de liquide des eaux provenant des résidus solides municipaux (RSM) ont augmentés par des facteurs respectifs de 1,61±0,05 et 1,39±0,01. Également, la DCOs biologique potentiellement disponible a augmenté jusqu'à 200%.

1 INTRODUCTION

Management of municipal solid waste (MSW) has been and continues to be a high priority for communities (Palmowski and Müller 2000). In the United States, approximately 251 million tons of MSW was generated in 2006, which almost 55 percent of that was disposed of in landfills (USEPA 2006b). Landfilling is still the most common way to dispose of solid waste in North America compared to other technologies. MSW consists of non-biodegradable and biodegradable fractions, where the latter is also called the organic fraction of municipal solid waste (OFMSW). The organic fraction of MSW has high moisture content, thus produces large amounts of leachate in landfills. If leachate is not treated properly, it can cause pollution to groundwater and negatively affect health and the environment. In the United States, anaerobic degradation of the organic material in landfills has resulted in them being the largest human-related source of fugitive methane (CH_4), accounting for 34% of all anthropogenic CH_4 emissions (USEPA 2006a). For these reasons, traditional landfilling is often not being considered as an option for management of organic waste in many countries.

Different technologies to treat OFMSW have been developed, such as incineration, composting and AD. Compared to the other two methods, anaerobic treatment of OFMSW is superior in both reducing the organic matter and producing usable energy (Schober et al. 1999; Mata-Alvarez 2003).

In the first step of AD, hydrolysis transforms suspended organic solid reactants to a more readily biodegradable soluble form to be metabolized by micro-organisms. For many high suspended solid substrates, hydrolysis is the slowest and the most rate-limiting step in the anaerobic biodegradation process (Pavlostathis and Giraldogomez 1991).

Various pre-treatment methods have been used in order to enhance hydrolysis and enhance the overall AD process. Methods such as, mechanical treatment (Hills and Nakano 1984; Muller et al. 1998; Hartmann et al. 2000; Palmowski et al. 2000; Sponza and Agdag 2005; Mshandete et al. 2006), ultrasound (Tiehm et al. 1997; Chu et al. 2001; Khanal et al. 2007; Akin 2008), chemical integration (Pavlostathis and Gossett 1985; Ray et al. 1990; Heo et al. 2003; He et al. 2008), thermal hydrolysis (Li and Noike 1992; Minowa et al. 1995; Schieder et al. 2000; Inoue et al. 2002; Wang et al. 2006; Bougrier et al. 2007; Jeong et al. 2007), and thermochemical pretreatment (Tanaka and Kamiyama 2002; Valo et al. 2004; DiStefano and Ambulkar 2006; Turker et al. 2008) have been investigated with varying degrees of success. Generally these pretreatment methods have successfully increased biodegradability of biomass and other organic wastes. In the case of OFMSW, conventional thermal pretreatment using high temperatures (160-175°C) and pressure (6-8MPa) have given the best AD performance in terms of improved rate and extent of degradation.

Thermal pre-treatment of food waste at 70ºC for 2 hours and at 150ºC for 1 hour was examined in a hybrid anaerobic solid–liquid system (Wang et al. 2006). The thermally pre-treated food waste halved the time to produce the same quantity of methane in comparison with AD of untreated food waste. In the case of canteen and gastronomic solid waste, temperatures between 160 and 200ºC, pressures up to 4 MPa and residence times of up to 60 min was the most successful pre-treatment for improved AD (Schieder et al. 2000). Laboratory digestion tests also demonstrated that hydrolysis of thermally pretreated waste was significantly faster, and biogas production also was higher in comparison to AD of mashed untreated waste.

Microwaves are an electromagnetic radiation that can oscillate electric dipole molecules such as water when exposed to a MW field. Water molecules rotate as they try to align themselves with alternating magnetic field which causes moisture in the material to heat up. The main difference between MW and conventional heating is that in the former temperature increases from the outside to inside the body as energy transfers from the outer surface but with MW irradiation the body temperature increases from within (Plazl et al. 1995). Dipole rotation and subsequent heating effects can also break apart weak hydrogen bonds and make complex organic molecules unfold and become smaller (Kingston and Jassie 1988; Loupy 2002) potentially making them more readily biodegradable.

Eskicioglu et al. (2007) investigated, low temperature (50-96ºC) MW irradiation of secondary sludge. Results showed that microwaved waste activated sludge (WAS), taken from an activated sludge unit operating at 5d solid retention time (SRT), had 3.6 and 3.2 fold increases in sCOD/tCOD ratio and 13% and 17% increases in cumulative biogas production (CBP) at concentrations of 1.4 and 3% TS, respectively, with similar improvement in VS destruction compared to controls.

He and Wen (2008) studied enhancing enzymatic digestibility of switchgrass by microwave-assisted alkali pretreatment. In this study, MW was used to pretreat switchgrass, which was then hydrolyzed by cellulase enzymes. When switchgrass was soaked in water and treated by MW, total sugar yield from the combined treatment and hydrolysis was 34.5 g/100 g biomass (58.5% of the maximum potential sugars released). This yield was 53% higher than conventional heating of switchgrass.

In the present study MW as an emerging energy efficient technology is used to pretreat OFMSW. The main objective of this study is to determine the effects of MW irradiation on solubilization of OFMSW at different temperatures, MW ramp times, and supplemental water addition (SWA).

2 MATERIALS AND METHODS

2.1 Organic waste

Since real OFMSW discharged from domestic houses and food processing industries usually has various properties, model OFMSW (M-OFMSW) was used to prevent any effects due to compositional variations. The components of M-OFMSW used were cooked rice (18 wt %), cooked pasta (18 wt %), cabbage (11 wt %), carrot (11 wt %), apple (11 wt %), banana (11 wt %), cooked ground beef (10 wt %) and dog food (10 wt %). Moisture content of M-OFMSW was 78.6±0.4%. The composition M-OFMSW was based on the literature (Cho et al. 1995; Minowa et al. 1995; Sawayama et al. 1999; Palmowski et al. 2000; Luostarinen and Rintala 2007) and Canada's Food Guide (CFG 2007) and was judged to be a good representation of kitchen waste in Canada. A kitchen aid food processor was used to reduce the particle size and homogenize the sample for further digestion. The M-OFMSW was supplemented with tap water depending on experimental conditions to give SWA of 20 and 30 % in the final M-OFMSW.

2.2 Microwave

A laboratory scale MW Accelerated Reaction System (Mars 5®, CEM Corporation) was used to pretreat the OFMSW.

2.3 Experimental Design

A statistical design using multilevel factorial design was applied (Berger and Maurer 2002) and the variables were chosen to be treatment temperature, SWA and temperature ramp time (MW intensity inversely proportional to ramp time). Table 1 shows the variables and their levels. The holding time at the final temperature is one minute for all experiments.

Table 1: Variable and their levels used in statistical design

Levels	Temperature	Temperature Ramp	SWA
1	115ºC	20 min	20 %*
2	145ºC	40 min	30 %**
3	175ºC	60 min	

* 80g M-OFMSW + 20g water
** 70g M-OFMSW + 30g water

Haug et al. (1978) observed that in thermal pretreatment, temperature has a clear effect on biodegradability. With activated sludge, biodegradability increased with temperature to an optimum near 175ºC, beyond which gas production decreased. Also a reaction temperature of 175ºC was preferable for the liquidization of OFMSW prior to AD (Minowa et al. 1995; Inoue et al. 2002). For this reason, the MW experiments were performed between 115ºC and 175ºC. MW Ramp (MW intensity) and SWA were selected based on the results of the study of Toreci (2008).

The properties of high temperature MW treated M-OFMSW were compared with untreated M-OFMSW in order to explore the effect of MW irradiation on potential influent substrate for subsequent AD.

2.4 Analytical Methods

pH was measured using a Fisher Accumet pH meter 750. TS and VS were determined based on Standard Methods procedure 2540 G. Alkalinity analysis were done according to Standard Methods 2320B titration method. Soluble COD measurements were conducted according to Standard Methods 5220C colorimetric method. Volatile fatty acids (VFAs; acetic, propionic and butyric acids) were measured by injecting supernatants into a HP 5840A gas chromatograph with a flame ionization detector and chromosorb 101 packed columns (Vanhuyss.Jj 1967). The concentration of soluble proteins and total soluble sugars were measured according to Frolund et al. (1995) and Benefield (1976), respectively. Bovine serum albumin (BSA) and glucose stock solutions were used as standards. Free water was determined by centrifuging 55 g of sample at 9000 RCF for 40 minutes and decanting and measuring the weight of the supernatant. Ultimate M-OFMSW solubilization was estimated using a severe chemical pre-treatment. 1g of M-OFMSW was added to 1L of NaOH (1N) and mixed for 24 hours. After 24 hours sCOD was measured (Bougrier et al. 2005).

3 RESULTS

The organic waste was microwaved at different conditions to determine changes in organic waste solubilization. Results from analysis of raw and irradiated organic waste are presented in Table 2. All samples were analyzed in triplicates. The effect of MW pretreatment on solubilization is presented in this section.

The highest increase in sCOD concentration was observed at 175ºC and 1MPa pressure. Microwave pretreatment for 20, 40, and 60 minutes ramp, respectively, resulted in 1.61±0.05, 1.62±0.01, 1.58±0.03 time higher sCOD concentrations with SWA of 30% (Figure 1) and 1.34±0.01, 1.38±0.03, 1.34±0.01 with SWA of 20% (Figure 2). The free liquid fraction of samples after using centrifuge with SWA of 20% was 1.51±0.02, 1.61±0.03, 1.67±0.03 time higher than control for 20, 40, and 60 minutes ramps, respectively. These ratios were 1.39±0.01, 1.34±0.02, 1.37±0.01 for samples with SWA of 30%. This signifies transformation of materials from solid to liquid phase. Considering both effects of increasing sCOD concentration and free liquid fraction available after MW pretreatment, it was concluded that the total sCOD available in the system was more than 2 times that in control samples. Higher SWA (40 and 50%) were also examined, but the mass of sCOD available in the system was less than 20 and 30% SWA. Water is the only ingredient that interacts with microwave electric field thus more water can increase the effectiveness of the radiation; however there is a practical limit for water content. Water content higher than this limit decreases rate of liquefaction. In a study by Eskicioglu et al. (2007) activated sludge pretreated by microwave with 5.4% TS showed higher sCOD/tCOD ratios than 1.4% TS.

Effect of MW ramp times on solubilization was more pronounced for treatment temperatures of 115ºC and 145ºC. The maximum effect of ramp was observed at pretreatment temperature of 145ºC and SWA of 20%. In this condition sCOD and liquid fraction increased 21% and 26%, respectively, when 60 minutes ramp was used instead of 20 minutes. At MW pretreatment temperature of 175ºC and 20% SWA the sCOD concentration and free water fraction increased by 0% and 10% respectively, when MW exposure was increased from 20 minutes to 60 minutes. These results suggest that for higher temperature, MW intensity has less impact on M-OFMSW solubilisation than lower MW exposure temperatures.

Ultimate M-OFMSW solubilization results in 1.89±0.08 and 1.85±0.03 fold increase in sCOD concentration (compared to control) for SWA of 20% and 30%, respectively. For 175ºC and SWA of 20 and 30% for all ramp times (ramp time at 175ºC had negligible effect on solubilisation) the highest degree of disintegration (Schmitz et al. 2000) was found to be 43 and 72% respectively. At 115ºC and 145ºC degree of disintegration ranged between 14-33% and 11-65 % respectively depending on ramp time and SWA.

Results for soluble sugar concentration (Table 2) do not demonstrate any specific trend for 20% SWA. In general, SWA of 30% yielded slightly higher soluble sugar than 20%. Solubilization was always slightly higher at lower microwave intensity, possibly due to longer exposure time to the MW field. Soluble sugar concentration of samples with 30% SWA after MW showed an increase for 115ºC and 145ºC but a decrease for 175ºC. According to Stuckey and McCarty (1984), severe pretreatment conditions enhance the formation of refractory compounds. Some intermolecular reactions occur between solubilized compounds (i.e. sugars and proteins) which lead to the formation of complex substances.

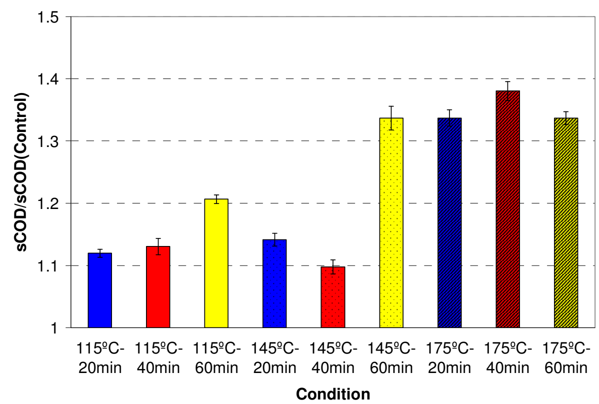

Figure 1: sCOD increase after MW for 20% SWA

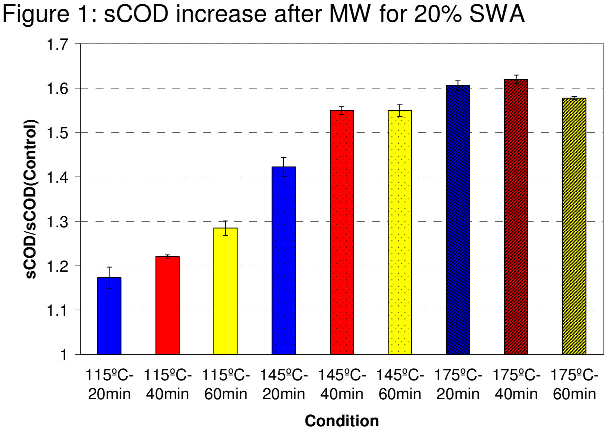

Figure 2: sCOD increase after MW for 30% SWA

Results of soluble protein concentration showed (Table 2) that increases in the temperature and MW ramp was accompanied by an increase in the soluble protein release. Soluble protein fraction was 5.4 fold higher than control at 175ºC and 60 minutes ramp, regardless of SWA. In general, protein solubilization was higher for samples with higher water content. The change in soluble sugar and protein are in good agreement with the change in sCOD in most cases, except sugar for high temperature (175ºC). Longer irradiation time resulted in a greater release of proteins and sugars from solid phase to liquid phase. This result supports the strong solubilization effect of MWs on WAS previously reported by Toreci (2008).

Table 2 depicts VS after thermal pretreatment. TS shows the same trend. VS reduction was more pronounced at higher temperature and water contents, indicating that significant volatilization was occurring at high temperature. VS reduction and ramp showed a mixed trend; probably VS reduction is proportional to ramp. One may conclude that thermal treatment, especially at high temperature, has considerable effects on VS reduction.

Total volatile fatty acids concentration increased during high temperature microwaving and exceeded 1000mg/L in the case of 175ºC. The effect of lower temperatures on VFA concentration is negligible. There is no pattern in VFA production; merely it increases at higher pretreatment temperature.

Alkalinity increased for low temperature MW pretreatment, vise versa it was zero for high temperature. As temperature and ramp increase the alkalinity and pH reduce as expected based on the higher VFA results resulting from high temperature MW pretreatment. As concentration of acids increase in the system alkalinity is consumed and pH drops to lower values.

Table 2: Organic waste properties before and after microwave treatment

Parameter.	SWA	Untreated OFMSW	115ºC			145ºC			175ºC		
			20 min	40 min	60 min	20 min	40 min	60 min	20 min	40 min	60 min
pH	20%	5.9	5.61	5.53	5.48	5.42	4.77	4.67	3.86	4.05	3.89
	30%	5.96	5.65	5.63	5.48	5.31	5.08	4.92	4.4	4.06	4.05
sCOD (g/Kg)	20%	92±1	103±2	104±3	111±2	105±2	101±2	123±3	123±1	127±2	123±1
	30%	71±1	83±2	87±1	91±1	101±3	110±1	110±2	114±3	115±0.5	112±2
TS (g/Kg)	20%	189±3	180±9	184±5	182±0	147±16	146±14	143±23	159±9	141±13	129*
	30%	167±28	151±29	156±2	157±0	134*	na**	125*	120±10	107±9	108±11
VS (g/Kg)	20%	182±4	173±9	177±4	175±0	141±13	140±0	138*	152±1	135±0	123*
	30%	160±1	145*	150±2	152±0	145	154±2	136*	115±2	103±4	103±0
Alkalinity (mg $CaCO_3$/Kg)	20%	462±17	650±0	850±71	650±35	663±18	325±0	0	0	0	0
	30%	413±17	600±35	550±35	588±17	375±0	0	0	0	0	0
TVFA* (mg/Kg)	20%	5	0	9	67	289	138	272	2028	1189	1451
	30%	4	0	7	9	155	250	198	647	1000	1275
Soluble protein (g/Kg)	20%	8.0±1.4	9.7±2.0	10.4±1.6	14.2±1.3	13.5±2.0	14.5±2.0	21.3±1.5	9.7±2.0	10.4±1.6	14.2±1.3
	30%	6.6±0.4	20.3±2.7	32.2±3.2	33.6±3.3	13.3±1.9	18.1±0.3	22.6±0.9	9.4±0.1	10.2±1.5	11.6±3.3
Soluble Sugar (g/Kg)	20%	94.8±4.9	93.3±4.4	90.5±1.5	109.9±5.7	91.4±7.3	92.6±4.6	122.4±6.1	92.9±6.3	105.2±2.7	102.8±8.5
	30%	82.3±3.0	86.8±1.9	90.4±1.8	105.6±3.7	97.4±1.9	104.9±4.6	108.7±3.9	92.9±6.4	91.0±3.9	89.0±2.1

*) Based on just one test result
**) not available

4 STATISTICAL ANALYSIS

The statistical package S-Plus® 8.0 was used to detect the significance of pretreatment factors in multilevel factorial design for organic waste solubilization by performing Analysis of Variance (ANOVA). Factorial ANOVA is used as it is required to study the effects of three treatment variables, which are temperature (T), MW ramp (R) and supplemental water addition (SWA).

ANOVA can provide information on the relative importance of each parameter with respect to others and show interactions between parameters of concern. The response variable was the ratio of sCOD and control sCOD ($sCOD/sCOD_{Control}$) and the independent variables were T, R and SWA. The ANOVA results are shown in Table 3.

In ANOVA analysis, p-value is the α-error for the hypothesis that the parameter plays a role in the model. P-value of three variables (T, R and SWA) is less than 0.05; therefore these three factors have significant effect on the waste solubilization at 95% confidence level. Between these parameters, the effect of ramp is less than temperature and SWA. Among the interaction parameters just T:SWA has significant effect on the waste solubilization at 95% confidence level and needed to be included in the model.

S-Plus® 8 was also used to fit the best empirical model to sCOD measurements, and quality of fit was evaluated. Linear model parameter estimations were done with two or three factor interactions. In order to improve the precision of models, parameters were centralized. Variables can be centered by subtracting the average values. For example if a model expressed as

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \quad [1]$$

where Y is the response (i.e., $sCOD/sCOD_{Control}$), β_i are the estimated parameters, X_i are variables (i.e., T, C and W) and ε is the residuals. Then the corresponding centralized variables model takes the form

$$Y = \beta_0^* + \beta_1^*\left(X_1 - \bar{X}_1\right) + \beta_2^*\left(X_2 - \bar{X}_2\right) + \beta_3^*\left(X_3 - \bar{X}_3\right) + \varepsilon \quad [2]$$

in which β_i^* are the estimated parameters and $\bar{X}_i$ are the average of the variables (i.e., $\bar{T}$, $\bar{C}$ and $\overline{SWA}$).

The fit level of models was compared together by using the coefficient of multiple determination or R^2 value. In order to compare different models with different number of parameters, R^2 value has to be adjusted to take into account improvements due to introducing more parameters. Adjusted R_a^2 is defined as

$$R_a^2 = 1 - \frac{n-1}{n-(k+1)}(1-R^2) \quad [3]$$

where n is the number of experiments, (k +1) is the number of parameters in the model.

Models with different structure were tested and the corresponding R^2 and R_a^2 shown in Table 5.

Table 3: Multifactor ANOVA for ($sCOD/sCOD_{Control}$)

Param.	DOF	Sum Of Squares	Mean of Squares	F Value	P value
T	2	0.3782	0.1891	41.6	0.0000
R	2	0.1059	0.0529	11.7	0.0006
SWA	1	0.3906	0.3906	86.1	0.0000
T:R	4	0.0443	0.0111	2.4	0.0841
T:SWA	2	0.0353	0.0176	3.9	0.0395
R:SWA	2	0.0031	0.0015	0.3	0.7175
T:R:SWA	4	0.0439	0.0110	2.4	0.0861
Residuals	18	0.0817	0.0045		

Table 5 shows that introducing more parameters into the models improves the overall fit based on R^2. This table also verifies that the best linear model (i.e., the highest R_a^2) is the fifth model which has 6 coefficients. However the second model with 5 coefficients can provide an almost similar fit based on the similar R_a^2 for models 2 and 5. Although the fifth model provides a slightly better fit compared to the second model, this improvement is small while it is a more complicated model concomitantly it was decided to select the second model as the best fit. The estimated parameters are shown in Table 4. In this table, the value of pr(>|t|) for the parameters proves that the estimation has been done with a very high confidence for β_0^*, β_1^* and β_3^*. The level of confidence is close to 95% for β_2^* and β_4^*. In general, it can be said the model is representative of the response with 95% confidence. The proposed model can be written as

$$Y = 1.124 - 0.003T + 0.002R - 0.023(SWA) + 0.0003T(SWA) \quad [4]$$

Table 4: Estimated coefficients values

Coefficient	Value	Std Error	t value	pr(>|t|)
β_0^*	1.341	0.017	78.863	0.000
β_1^*	0.005	0.001	6.894	0.000
β_2^*	0.002	0.001	2.146	0.050
β_3^*	0.021	0.003	6.116	0.000
β_4^*	0.0003	0.000	2.109	0.053

A comparison of the experimental data and the values predicted by the proposed model is presented in Figure 3. This figure clearly shows a sudden increase in the response ($sCOD/sCOD_{Control}$) when SWA increased from 20% to 30%. It also clearly shows a stepwise jump in the response in direct relation to the temperature.

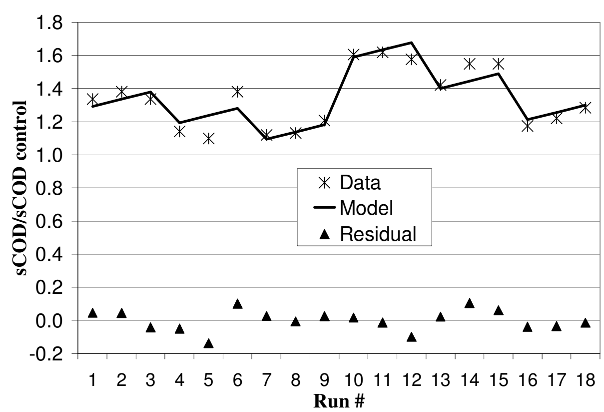

Figure 3: Comparison of the model and data

CONCLUSION

The feasibility of using MW for pretreatment and solubilisation of OFMSW prior to final waste stabilization has been verified using different operating conditions. Different temperatures, MW ramps and supplemental water additions were investigated. Based on experimental data, the following conclusions are drawn.

The highest increase in sCOD was achieved at 175ºC. MW pretreatment resulted in 1.61±0.05, 1.62±0.01, 1.58±0.03 time higher sCOD with SWA of 30% for 20, 40, and 60 minutes ramp, respectively. For the same conditions free liquid fraction was 1.39±0.01, 1.34±0.02, 1.37±0.01 time higher than control.

Changes in soluble total sugar did not show a specific trend, but it was slightly higher for 30% SWA and for longer MW ramp times. Soluble protein levels increased the greatest at higher temperature, long MW ramp and higher SWA.

Three factor fixed effect ANOVA showed that independently all three variable tested temperature, SWA and MW ramp have significant effects on COD solubilisation at a 95% confidence interval. Evaluation of T, R and SWA interactions showed that only T and SWA interactions were significant at the 95% confidence interval. A simple empirical model was determined and can be used to describe COD solubilisation over the range of T, R and SWA evaluated.

It can be concluded that microwaving of M-OFMSW at high temperature (175°C) with supplemental water addition provides the best conditions for waste solubilisation in preparation for AD. The actual effect of MW pre-treatment on the AD process has yet to be determined.

Table 5: Linear models for ($Y = \text{sCOD}/\text{sCOD}_{\text{Control}}$)

No	Linear Model	No. of parameters	R^2	R_a^2
1	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA})$	4	0.837	0.802
2	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA}) + \beta_4^*(T-\overline{T})(SWA-\overline{SWA})$	5	0.878	0.841
3	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA})$ $+\beta_4^*(R-\overline{R})(SWA-\overline{SWA}) + \beta_5^*(T-\overline{T})(R-\overline{R})$	6	0.850	0.788
4	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA})$ $+\beta_4^*(T-\overline{T})(SWA-\overline{SWA}) + \beta_5^*(R-\overline{R})(SWA-\overline{SWA})$	6	0.880	0.831
5	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA})$ $+\beta_4^*(T-\overline{T})(R-\overline{R}) + \beta_5^*(T-\overline{T})(SWA-\overline{SWA})$	6	0.890	0.844
6	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA})$ $+\beta_4^*(T-\overline{T})(SWA-\overline{SWA}) + \beta_5^*(T-\overline{T})(R-\overline{R}) + \beta_6^*(R-\overline{R})(SWA-\overline{SWA})$	7	0.892	0.833
7	$Y = \beta_0^* + \beta_1^*(T-\overline{T}) + \beta_2^*(R-\overline{R}) + \beta_3^*(SWA-\overline{SWA}) + \beta_4^*(T-\overline{T})(SWA-\overline{SWA})$ $+\beta_5^*(T-\overline{T})(R-\overline{R}) + \beta_6^*(R-\overline{R})(SWA-\overline{SWA}) + \beta_7^*(T-\overline{T})(R-\overline{R})(SWA-\overline{SWA})$	8	0.893	0.818

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