Extended ADM1 for Simulation of Anaerobic Digestion of Microwave Pre-Treated Sludge

Aboulfotoh A. M.
Environmental Eng. Dep., Faculty of Engineering,
Zagazig University,
Zagazig, Egypt

***Abstract*— Over the past decade the Anaerobic Digestion Model No1 (ADM1) proved to be a powerful tool for predicting and control of anaerobic digestion process, In this paper the ADM1 was extended for microwave pre-treated mixture of municipal primary and secondary sludge for different hydraulic retention times (HRT) of 20, 15, 10, 7, and 5 days using two scenarios the 1st scenario assuming one step digestion from raw sludge, while the 2nd scenario depends on the sludge characteristics after pre-treatment. The two proposed scenarios for all studied SRT was able to reflect the trends that were observed in the experimental results for the COD removal ratio and Biogas production rate while the two models were over predicted for VFAs for SRT more than 10 days. The proposed two models were then tested against another research results and give a good prediction values. The biochemical parameters values proposed by Batstone (k_{dis} = 0.40, k_{hydch} = 0.25, k_{hydpr} = 0.20, and k_{hydli} = 0.10) for control mesophilic digester needed to be modified for the 1st scenario to be (k_{dis} = 0.50, k_{hydch} = 0.50, k_{hydpr} = 0.50, and k_{hydli} = 0.50), and for the 2nd scenario to be (k_{dis} = 0.40, k_{hydch} = 0.325, k_{hydpr} = 0.325, and k_{hydli} = 0.325).**

Keywords*— ADM1; anaerobic digestion; biochemical parameters; biogas production; microwave pre-treatment.

I. INTRODUCTION

Anaerobic digestion plays an important role in wastewater treatment processes. It includes a series of biochemical processes by different microorganisms to degrade organic matter under anaerobic conditions. Methane, the digestion byproduct, is a rich source of renewable energy, which can help to replace fossil fuel to contribute to environmental conservation and sustainability [1]. A major benefit is the large volume reduction of the sludge. Other beneficial features include stabilization of the sludge, inactivation and reduction of pathogens, and improvement of the sludge dewaterability [2], which is very important for further handling after AD. The main problem related to sludge treatment is its cost which usually ranges from 20% to 60% of the total operating costs of the wastewater treatment plant [3].

Activated sludge is resistant to anaerobic digestion. The cell contents are very degradable but they are protected by the tough cell walls. Biomass also holds onto water, so it is difficult to dewater [4]. In this sense, a lot of research attention has been paid to pre-treatment methods that cause a disintegration of the sludge (accompanied by the solubilisation of organic material) and hence succeed in partially bypassing the hydrolytic stage and leading to a higher biogas production. Different techniques have been studied, including chemical [5], mechanical [6], ultrasonic [7], enzymatic [8] and thermal [9] treatments.

The microwave radiation is classed as thermal process, but it has so called non-thermal effects. The main advantage of microwave treatments is the rapid volumetric heating. Whereas the quantum energy of microwave radiation is too low to break the primary chemical bounds but the thermal effect of microwave irradiation could be manifested in the polarizing of macromolecules or breaking of hydrogen bounds. Therefore, for instance the microwave irradiated microbial cell shows greater damage than convective heating cells to a similar temperature [10].

II. MODEL DESCRIPTION

The ADM1 model is described in considerable detail in the report prepared by the IWA Task Group for Mathematical Modeling of Anaerobic Digestion Processes [11]. The following provides a brief overview of the model for the purposes of this discussion. The ADM1 model is a structured model that reflects the major processes that are involved in the conversion of complex organic substrates into methane and carbon dioxide and inert by-product In Fig. 1 an overview of the substrates and conversion processes that are addressed by the model is presented. From Fig. 1 it can be seen that the model includes disintegration of complex solids into inert substances, carbohydrates, proteins and fats. The products of disintegration are hydrolyzed to sugars, amino acids and long chain fatty acids (LCFA) respectively. Carbohydrates and proteins are fermented to produce volatile organic acids (acidogenesis) and molecular hydrogen. LCFA are oxidized anaerobically to produce acetate and molecular hydrogen. Propionate, butyrate and valerate are converted to acetate (acetogenesis) and molecular hydrogen. Methane is produced by both cleavage of acetate to methane (aceticlastic methanogenesis) and reduction of carbon dioxide by molecular hydrogen to produce methane (hydrogenotrophic methanogenesis).

In ADM1 the input substrate is described through 28 variables. These are concentrations of 12 dissolved and 12 particulate substances, concentration of cations and anions, liquid flow speed and temperature. Three additional parameters are needed to describe the state of the reactor. These are concentrations of H_2, CH_4 and CO_2 in headspace [12].

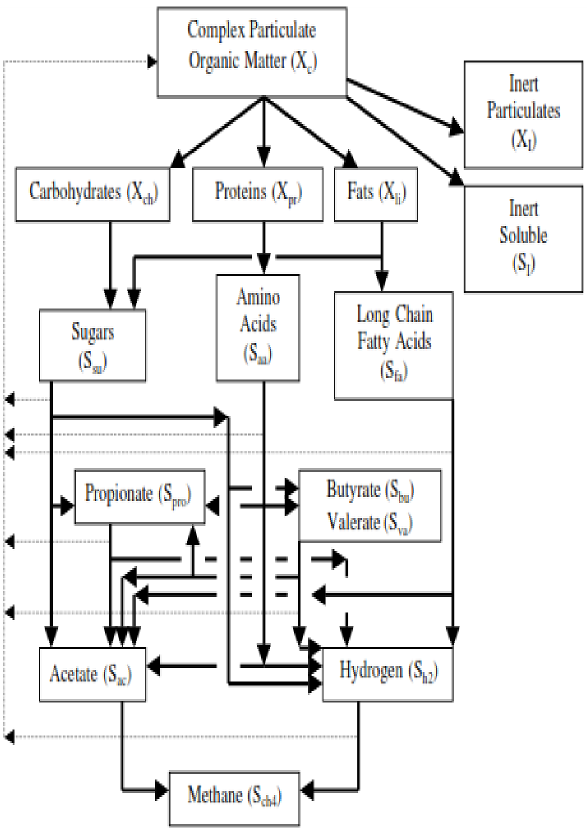

Fig.1 Conceptual model for ADM1 model

Since its establishment, a lot of updates and extensions have been suggested for the model. A few of them, as well as some criticisms have been noted [13]. Reference [14] discusses some issues concerning the materials balance of C and N in ADM1.

A. ADM1 Implementation

The model equations were implemented in the Matlab/Simulink platform version 7.8 according to the approach described in [14]. All reactions, apart from the calculation of pH, are implemented as ordinary differential equations (ODE). As suggested by the same authors, the acid-base equilibrium is calculated using a nested routine in which the concentrations of acetate, butyrate, valerate, propionate, ammonium and hydronium are calculated. All kinetic and stoichiometric parameters used in the model, are listed in the original model proposed by Batstone. The ADM1 is a stiff model; a system is called stiff, when the range of the time constants is large. This means that some of the system states react quickly whereas some react sluggishly. The ADM1 is a very stiff system with time constants ranging from fractions of a second to months. This makes the simulation of such a system challenging and in order to avoid excessively long simulation times, one need to be somewhat creative when implementing the model. The best used solver for this model is the ODE 15s [15]. The ADM1 implementation in this paper were tested against the data in [14] as they give a complete influent and effluent parameters for their implementation, the tested implementation prove to be a accurate for all effluent parameters.

III. Model Calibration and Extension

In this study two selected data sets were chosen from previously published reports on microwave pre-treatment of municipal wastewater sludge with mesophilic anaerobic digestion. The first selected data set [16] was selected as it studied the performance of anaerobic digesters in the semi continuous phase with and without microwave pre-treatment and over a set of SRT ranged from 5 to 20 d so these data were used to calibrate the model for the control reactors and then developed and extend the model for the microwave pre-treatment. The second data set [17] was then used to validate the extended model as it used the same microwave operating temperature of 80 0c. Also the COD and VS concentrations were much higher than the values of the first selected data set as will shown blow.

A. Model calibration

Reference [16] reported a study that assessed the impact of microwave pre-treatment and digester SRT on mesophilic anaerobic digestion of mixed PS and WAS. A series of digesters were operated over SRTs ranging from 5 to 20 days. The characteristics of raw, and microwave pre-treated sludge used in their paper are summarized in table 1.

Table 1. Characteristics of raw, and microwave pre-treated sludge [16]

Parameters	**Concentration (mg/L)**	
	Raw sludge	***Microwave pre-treated sludge***
TS	15651 ± 801	15801± 945
VS	10015 ± 642	10030 ± 455
COD	120721 ± 1251	12304 ± 1426
CODs	466 ± 148	1518 ± 197
Acetic acid	216 ± 58	242 ± 30
Propionic acid	115 ± 53	136 ± 45
Iso-butyric acid	57 ± 7	58 ± 6
Butyric acid	63 ± 4	64 ± 5
Valeric Acid	88± 20	89 ± 18

B. Control digester model

The comparison of the model predictions and the actual control digester performance for pH, COD removal ratio, biogas production, and VFAs is summarized in Fig. 2. It can be seen that the model was under estimated for the pH value but the difference was acceptable as the actual and predicted pH value was in the optimum range. The model was able to predict the effluent COD with High accuracy for all SRTs, The Actual COD removal ratio for the control digester was between 21.5% and 38.1% while for the model the ratio ranged between 23.53% and 38.5%. And Regarding the biogas production whoever being under estimated from the model as the actual biogas production was ranged between 0.18 (L/L/d) and 0.36 (L/L/d), the biogas production from the model was between 0.14 (L/L/d) and 0.30 (L/L/d), but the model over predicted the percent composition of Methane as the actual value ranged between 58.40 % and 60.4 % while the predicted value ranged between 67 % and 70%.

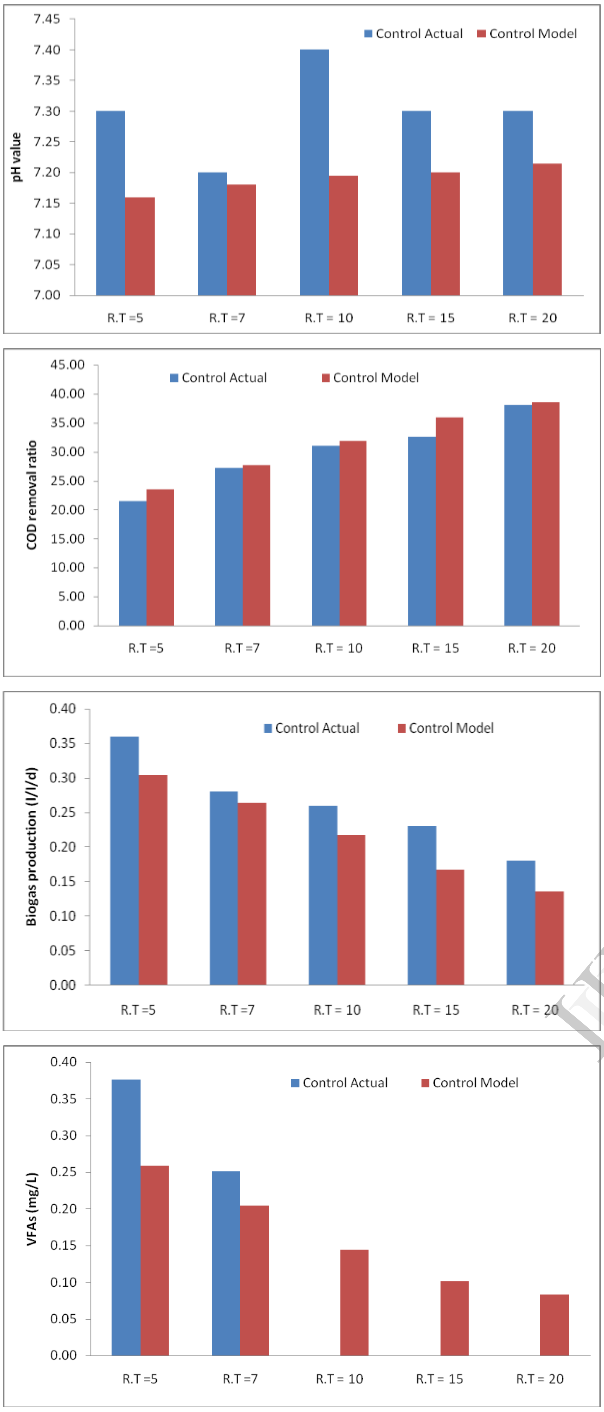

Fig.2 Actual and predicted (pH value, COD removal ratio, Biogas production and VFAs) for the control digester

For VFAs the model was over predicted for the longer SRT as the actual measures did not found any VFAs while the model predicted a small concentrations ranged between 80 (mg/L) and 140 (mg/L), also the VFAs values are in the range between 50 and 300 mg/l which is an indication of good digestion the results predicted by the model complied with the results published in [18] and [2].

C. Microwave pre-treated sludge digester model

In order to extend the ADM1 model for the prediction of microwave pre-treatment two scenarios were tested the 1st scenario (MW model 1) assuming one step digestion from raw sludge –the characteristics of the raw sludge were used as inputs for the model-, while the 2nd scenario (MW model 2) depends on the sludge characteristics after pre-treatment –the characteristics of the pre-treated sludge were used as inputs for the model-. Batstone in the original model order the sensitivity parameters of the model and consider the most sensitive parameter to be disintegration and hydrolysis parameters. So after recalculating different combinations for disintegration and hydrolysis parameters the combinations presented in Table 2 are considered to be the most optimal for the two proposed scenarios under study in this research.

TABLE 2. Estimated parameters values for the untreated sludge (US) and the microwave pre-treated sludge (MW) two scenarios

Parameters	**Concentration (mg/L)**		
	US	***MW 1***	***MW 2***
K_{dis}	0.40	0.50	0.40
K_{hydch}	0.25	0.50	0.325
K_{hydpr}	0.20	0.50	0.325
K_{hydli}	0.10	0.50	0.325

The comparison of the two models predictions and the actual MW digester performance for pH, COD removal ratio, biogas production, and VFAs is summarized in Fig. 3. It can be seen that each model of the two proposed models has a strength point and another weakness point against the other model, the MW model 2 was stronger than model 1 in the prediction of the pH value and gives almost the actual measured value except for SRT of 10 days while the MW model 1 under estimated the pH values but also the actual and two predicted pH value was in the optimum range for methane production (6.5 – 7.5), the two models predict the COD removal ratios by acceptable values, The Actual COD removal ratio for the MW digester was between 32.80% and 50.70% and for MW model 1 the ratio ranged between 36.80% and 49.70% while for MW model 2 the ratio ranged between 34.35% and 48.85%, the MW model 1 was stronger in the estimation of the biogas production as the actual biogas production was ranged between 0.22 (L/L/d) and 0.55 (L/L/d), the biogas production from MW model 1 was between 0.18 (L/L/d) and 0.51 (L/L/d), the biogas production from MW model 2 was between 0.16 (L/L/d) and 0.41 (L/L/d), the actual (%CH4) was between 59.00 % and 60.8 % while the for the two models the predicted values ranged between 68 % and 71%. While for all SRTs the two models over predicted the VFAs concentrations while MW model 1 predictions was lower than MW model 2 prediction for all SRTs.

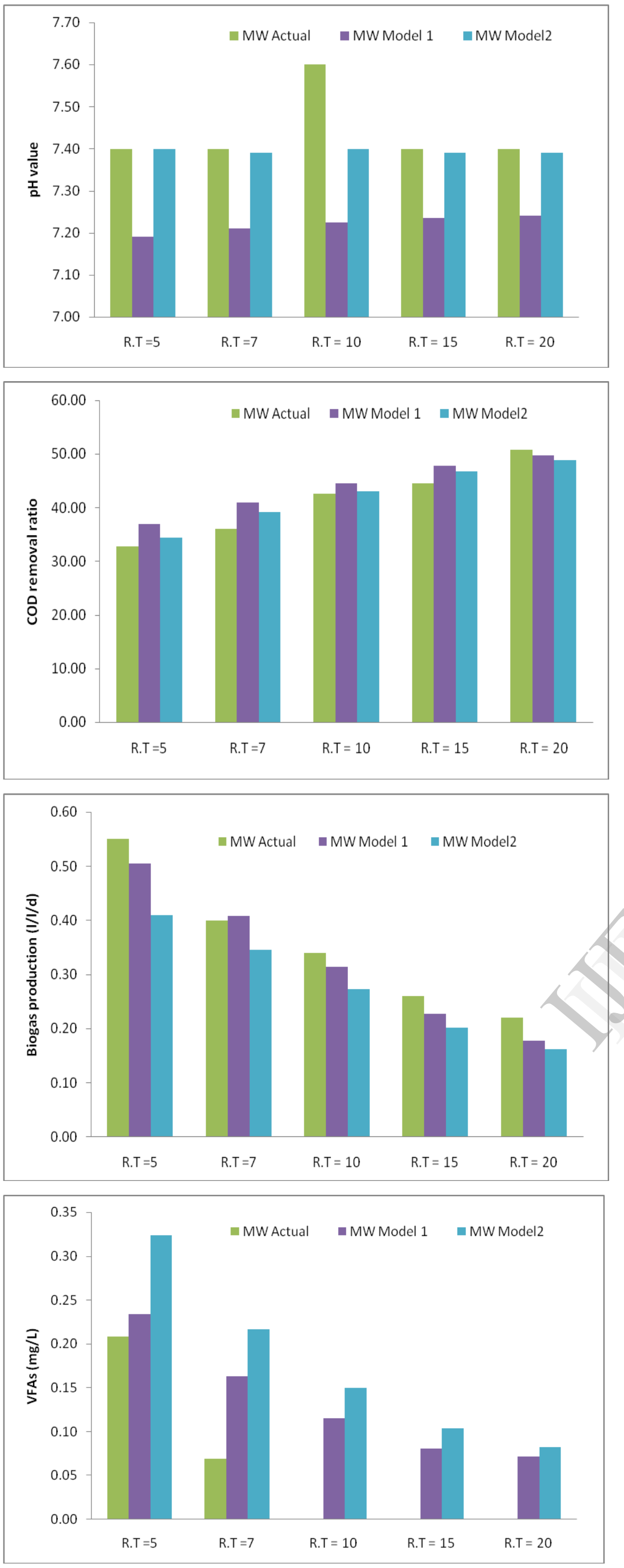

Fig.3 Actual and two predicted (pH value, COD removal ratio, Biogas production and VFAs) for the microwave pre-treated digester.

D. Model validation

Reference [17] reported a study that assessed the impact of microwave pre-treatment on mesophilic anaerobic digestion with SRTs of 20 d and receiving a thickened mixed PS and WAS. The characteristics of raw, and microwave pre-treated sludge used in their paper are summarized in table 3.

TABLE 3. Characteristics of raw and microwave pre-treated sludge [17]

Parameters	**Concentration (mg/L)**	
	Raw sludge	***Microwave pre-treated sludge***
TS	40080 ± 8000	40500± 8200
VS	28500 ± 5400	28100 ± 5700
COD	45331 ± 12064	46008± 11853
CODs	1353± 648	4247 ± 816
Acetic acid	1040 ± 576	1103 ± 167
Propionic acid	351 ± 333	298 ± 151
Iso-butyric acid	42± 39	157 ± 163
Butyric acid	70 ± 70	319 ± 788
Valeric Acid	130± 104	367 ± 213

The comparison ratio -value of the MW digester over the control digester values- of the two models predictions and the actual MW digester performance for COD removal ratio, biogas production, and VFAs is summarized in Fig. 4. It can be seen that the two models predict the COD removal ratios by acceptable values, The COD removal ratio for the MW digester was higher than the control digester by 20.0% and for MW model 1 the ratio was 27.0% while for MW model 2 the ratio was 22.0%, using MW increased the actual biogas production as the actual biogas production by 50.0%, and for MW model 1 the ratio was 29.0% while for MW model 2 the ratio was 32.0%. While the VFAs were under estimated this is may be due to the high initial values of COD, CODs and VFAs.

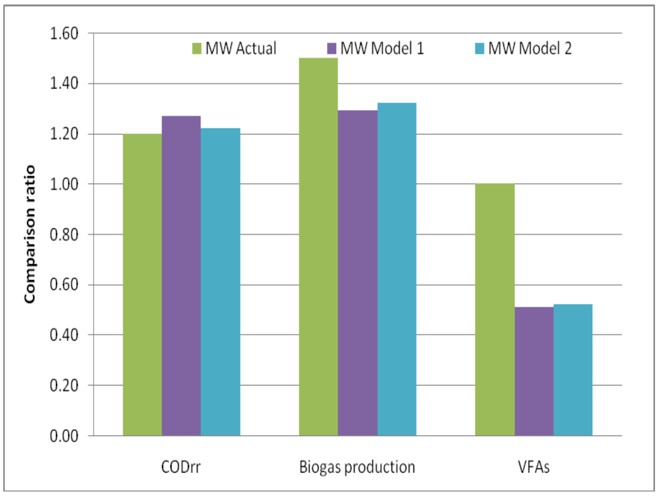

Fig.4 Actual and two Predicted comparison ratios for COD removal ratio, Biogas production and VFAs for the second data set

ISSN: 2278-0181
Vol. 3 Issue 2, February - 2014

IV. CONCLUSION

In this paper, An implementation of the ADM1 model was tested in order to describe the behavior of mesophilic anaerobic digester, The ADM1 proved to be powerful tool for the prediction and control of mesophilic anaerobic digesters as the model predicted the behaviour of the control digesters with reasonable values for pH value, COD removal ratio, biogas production, and VFAs, two extension seniors were then tested to describe the effect of microwave pre-treatment on the degradability of sludge, The biochemical parameters values proposed by Batstone (k_{dis} = 0.40, $_{khydch}$ = 0.25, k_{hydpr} = 0.20, and k_{hydli} = 0.10) for control digester needed to be modified for the 1st scenario to be (k_{dis} = 0.50, k_{hydch} = 0.50, k_{hydpr} = 0.50, and k_{hydli} = 0.50), and for the 2nd scenario to be (k_{dis} = 0.40, k_{hydch} = 0.325, k_{hydpr} = 0.325, and k_{hydli} = 0.325). The two extended models also gave good and acceptable values for the tested parameters, while a further investigation and testing is required for the extended model.

REFERENCES

[1] Pavlostathis, S.G. and Giraldo-Gomez, E. (1991) Kinetics of anaerobic treatment: A critical review. Critical Reviews in Environmental Control 21(5-6), 411-490.

[2] Appels, L., Degrève, J., Van der Bruggen, B., Van Impe, J., Dewil, R., (2010). Influence of low temperature thermal pre-treatment on sludge solubilisation, heavy metal release and anaerobic digestion. Bioresour. Technol. 101, 5743–5748.

[3] Marcos von Sperling: Carlos A. Chernicharo, (2005). “Biological wastewater treatment in warm climate regions”. IWA Publishing, USA.

[4] Garg, N.K (2009) “Multi-criteria Assessment of Alternative Sludge Disposal Methods” M.sc. thesis, University of Strathclyde, Scotland.

[5] Dewil, R., Appels, L., Baeyens, J. and Degrève, J. (2007). Peroxidation enhances the biogas production in the anaerobic digestion of biosolids. Journal of Hazardous Materials, 146, 577-581.

[6] Zhang, S., Zhang, P., Zhang, G., Fan, J., Zhang, Y., (2012). Enhancement of anaerobic sludge digestion by high-pressure homogenization. Bioresour. Technol. 118, 496–501.

[7] Bougrier, C., Carrère, H., Degenès, J.P., (2005). Solubilisation of waste-activated sludge by ultrasonic treatment. Chem. Eng. J. 106, 163–169.

[8] Aboulfotoh A. M . " ADM1 Simulation of the Mesophilic Anaerobic Digestion of Mixture of Primary and Secondary Sludge Treated by Effective Microorganisms ", Vol.2 - Issue 10 (October - 2013), International Journal of Engineering Research & Technology (IJERT) , ISSN: 2278-0181 , www.ijert.org.

[9] Val del Río, A., Morales, N., Isanta, E., Mosquera-Corral, A.Campos, J.L., Steyer, J.P.,Carrère, H., (2011). Thermal pre-treatment of aerobic granular sludge: impact on anaerobic biodegradability. Water Res. 45, 6011–6020.

[10] Jones, D.A., Lelyveld, T.P., Mavrofidis, S.D., Kingman, S.W., Miles, N.J., (2002). Microwave heating applications in environmental engineering – a review. Resour. Conserv. Recyl. 34 (2), 75–90.

[11] IWA 2002. Anaerobic Digestion Model No. 1 (ADM1), International Water Association Scientific and Technical Report No. 13, IWA Publishing, London, UK.

[12] Normak A.; Suurpere J.; Orupõld K.; Jõgi E.and Kokin E. (2012) “Simulation of anaerobic digestion of cattle manure”, Agronomy Research Biosystem Engineering Special Issue 1, 167-174.

[13] Batstone, D.J., Keller, J. and Steyer, J.P. (2006). A review of ADM1 extensions, applications and analysis: 2002-2005. Water Science & Technology, 54(4), 1-10.

[14] Rosen, C. and Jeppsson, U. (2006). Aspects on ADM1 Implementation within the BSM2 framework. IWA BSM TG Technical Report (available at www.benchmarkwwtp.org).

[15] Oscar Lidholm (2008) “Modeling Anaerobic Digestion -Validation and calibration of the Siegrist model with uncertainty and sensitivity analysis” M.Sc. thesis, Lund University, Sweden.

[16] Woon-Ji Park, Johng-Hwa Ahn (2011)” Effects of Microwave Pretreatment on Mesophilic Anaerobic Digestion for Mixture of Primary and Secondary Sludges Compared with Thermal Pretreatment”, Environ. Eng. Res., 16(2): 103-109.

[17] Appels L., Houtmeyers S., Degrève J., Impe J.V., Dewil R. (2013). “Influence of microwave pre-treatment on sludge solubilization and pilot scale semi-continuous anaerobic digestion” Bioresource Technology 128, 598–603.

[18] Parker W.J. (2005) "Application of ADM1 model to advanced anaerobic digestion", Bioresource Technology 96, 1832–1842.