International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Research Article

Comparison between the Steady State Anaerobic Digestion Model and ADM1 for Anaerobic Digestion of Sewage Sludge

Aboulfotoh A. M.[Ȧ*] & Ali A. M.[Ȧ]

[Ȧ]Environmental engineering department, Faculty of engineering, Zagazig University, Zagazig, Sharkia, 44519, Egypt.

Accepted 01 March 2014, Available online 01 April 2014, **Vol.4, No.2 (April 2014)**

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, while the approach of characterizing sewage sludge into carbohydrates, lipids and proteins requires measurements that are not routinely available on sewage sludge and so The ADM1 model has been regarded as too complex for practical applications. The main purpose of this research was to assess the steady state model against the ADM1 in order to determine the possibility of using it for anaerobic digestion of different types of sewage sludge such as primary sludge, mixture of primary sludge and waste activated sludge, and mixture of primary sludge and trickling filter sludge. The steady state model was able to predict the effluent COD concentration, Biogas production and pH value of all types of tested sludge used in this research paper and the results showed a lack of significant difference between the steady state model predictions and the ADM1 predictions. Therefore, the steady state model proposed by Sotemann preferred to be used for the simulation and modeling of the anaerobic digestion of any type of sewage sludge –in case of steady state operation- because of its ease and its applicability.

Keywords: *ADM1, anaerobic digestion, biogas production, sewage sludge, Steady state model,*

1. Introduction

Anaerobic digestion is a multi-step process involving the action of multiple microbes. Usually, such processes contain a particular step, the so called rate-limiting or rate-determining step, which, being the slowest, limits the rate of the overall process. Anaerobic digestion has traditionally been treated as a black box system due to the complexity of the process. To facilitate design, system analysis, operational analysis and control, a mathematical model describing the processes is required (Batstone, 2006). The different purposes require different ranges of accuracy and model complexity. A complex, non-linear model with focus on the biochemical reactions is well suited when the understanding of the process is important, e.g. for operational analysis or for research purposes. These models can facilitate optimization of operational stability and efficiency. When implementing model-based control on a system, a linear and well parameterized model is needed with measurable key parameters as input signals. For design purposes, the model should focus on hydraulics and particle structure (Batstone, 2006). An example of such a model is presented in Elmitwalli et al. (2003).

Over the years a range of models have been developed for modeling of the anaerobic digestion processes. Early models were steady state and assumed a rate-limiting step (Lawrence 1971). However, the increasing complexity of the advanced digestion technologies requires more complex models that can represent the impacts of changing environments on chemical and microbial species. (Siegrist, et. al.,1993). Relatively recently there has been a move by the International Water Associations (IWA) Task Group for Mathematical Modeling of Anaerobic Digestion Processes to develop a common model that can be used by researchers and practitioners (IWA 2002). This model (ADM1) has a structure that is similar to the IWA activated sludge models that have received acceptance by practitioners over the last 10 years (Parker 2005). The approach of characterizing sewage sludge into carbohydrates, lipids and proteins, as is done in the ADM1 requires measurements that are not routinely available on sewage sludge (Sotemann et al 2005, a).

Sotemann et al (2005 b, c) developed a simple model, in which the sewage sludge feed is characterized in terms of total COD, its particulate un-biodegradable COD fraction (f_{upf}), the short chain fatty acid (SCFA) COD and the CHON content, i.e. X, Y, Z and A in $C_XH_YO_ZN_A$ of the particulate organics. This approach characterizes the sludge in terms of measurable parameters in conformity with the COD, C and N mass balances approach. With this approach, the interactions between the biological processes and weak acid/ base chemistry could be correctly predicted for stable steady state operation of anaerobic digesters.

This research paper focuses on the examination of the steady state model against the ADM1 for anaerobic

*Corresponding author: **Aboulfotoh A. M.**

digestion of different types of sewage sludge such as primary sludge, mixture of primary sludge and waste activated sludge, and mixture of primary sludge and trickling filter sludge.

2. Model description

2.1 The Steady state anaerobic digestion model

Sotemann et al (2005a, b) developed an integrated two-phase (aqueous-gas) mixed weak acid base chemical, physical and biological processes kinetic model for anaerobic digestion (AD) of sewage sludge. The COD, C and N mass balances and continuity basis of this model fixes quantitatively, via the interrelated chemical, physical and biological processes, the relationship between all the compounds of the system. Thus for a given sewage sludge COD removal the digester out puts (i.e. effluent COD, TKN, FSA, SCFA, H_2CO_3* Alk, pH, gaseous CO_2 and CH_4 production and partial pressures) are governed completely by the input sludge solids (and dissolved) constituents.

In the reaction scheme of Gujer and Zehnder (1983) Figure (1), the hydrolysis process acts separately on three main groups of complex organics, proteins, carbohydrates and lipids. These complex polymeric materials are hydrolyzed by extra-cellular enzymes to soluble products that are small enough to allow their transport across the cell membrane.

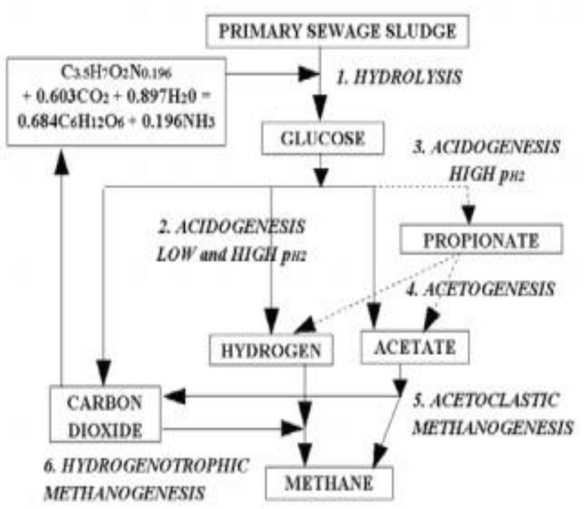

Fig. 1 anaerobic digestion processes scheme of (UCTADM1) including (i) the effect of high hydrogen partial pressure on acidogenesis and (ii) COD, carbon and nitrogen mass balances with a generic CHON sludge composition.

The products of the separate hydrolysis processes are amino acids, sugars and fatty acids respectively. These relatively simple, soluble compounds are fermented (Acidogenesis) or an-aerobically oxidized to short chain fatty acids (SCFAs) (acetate), alcohols, CO2, hydrogen and ammonia. A portion of the hydrolysis products are also converted to inter mediate products (propionate, butyrate, etc.), which are then converted to acetate, hydrogen gas and CO2 through a process called acetogenesis. Lastly, Methanogenesis occurs by hydrogen reduction with CO2 (hydrogenotrophicmethanogenesis) and from acetate cleavage (acetoclasticmethanogenesis

The steady state model considers three aspects:

1. The kinetics of the hydrolysis/acidogenesis process.
2. Stoichiometry conversion of the products from (1) to digester end-products
3. The effect of the end products on the digester pH (weak acid/base chemistry).

Since the hydrolysis/acidogenesis process is the slowest one in the sewage sludge anaerobic digester and does not reach completion within the normal range of the principal digester design parameter of hydraulic retention time, a kinetic expression describing this process rate is required for the steady state model. Sötemann et al. (2005a) considered four kinetic equations for this process:

- First order with respect to the residual biodegradable particulate organic (COD) concentration S_{bp},
- First order with respect to S_{bp} and the acidogen biomass concentration (Z_{AD}) which mediates this process,
- Monod kinetics,
- Saturation (or Contois) kinetics

Aboulfotoh (2012) in his study found that the modeling using a first order with respect to the residual biodegradable particulate organic (COD) concentration S_{bp} was the most suitable for the anaerobic digestion of a mixture of primary and waste activated sludge, so it will be under investigation in this paper. For more details about the model equation and implementation refer to Sotemann et al (2005 a, b and c) and Aboulfotoh (2012).

2.2 ADM1

The ADM1 model is described in considerable detail in the report prepared by the IWA Task Group for Mathematical Modeling of Anaerobic Digestion Processes (IWA, 2002). 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 byproduct In Figure 2 an overview of the substrates and conversion processes that are addressed by the model is presented. From Fig. 2 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 (aceticlasticmethanogenesis) and reduction of carbon dioxide by molecular hydrogen to produce methane (hydrogenotrophicmethanogenesis).

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 (Normak et al., 2012).

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 by Batstone et al. (2006). Rosen &Jeppson (2006) discuss some issues concerning the materials balance of C and N in ADM1.

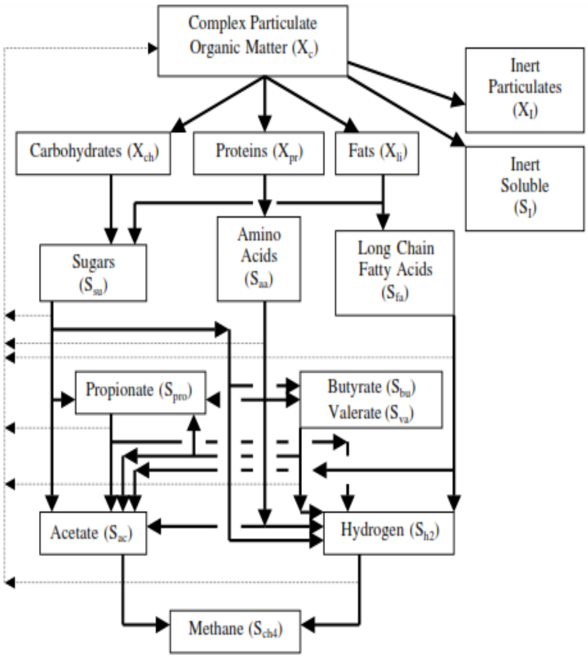

Fig.2 Conceptual model for ADM1 model

The model equations were implemented in the Matlab/Simulink platform version 7.8 according to the approach described in Rosen &Jeppsson (2006). For more details about the model equation and implementation refer to Aboulfotoh (2013).

3. Models testing and comparison

In this study three selected data sets were chosen from previously published reports on anaerobic digestion of sewage sludge, representing three types of sludge [primary sludge, mixture of primary sludge and waste activated sludge, and mixture of primary sludge and trickling filter sludge]. the primary sludge and the mixture of primary and trickling filter sludge were used by Sotemann et al (2005 b,c) to determine the hydrolysis kinetics of the steady state model, while the mixture of primary and waste activated sludge were studied by one of the authors of this paper.

3.1. Primary sludge digestion

O'Rourke (1967) studied the kinetics of anaerobic sludge treatment at ambient temperatures, since at the time, most AD systems were operated at 35 C, and little was known about the performance of the systems at ambient temperatures. To determine the kinetics of AD at the ambient temperatures and the influence of temperature, digesters were fed a primary sludge concentration of 28.4 (gCOD/l) and operated at 35, 25, 20 and 15°C and hydraulic retention times from 60 d to as low as 2.75 d, in which methanogenesis had failed. For this evaluation, only the methanogenic systems operated at 35 C are considered, of which there were five, i.e. 7.5, 10, 15, 30 and 60 d systems.

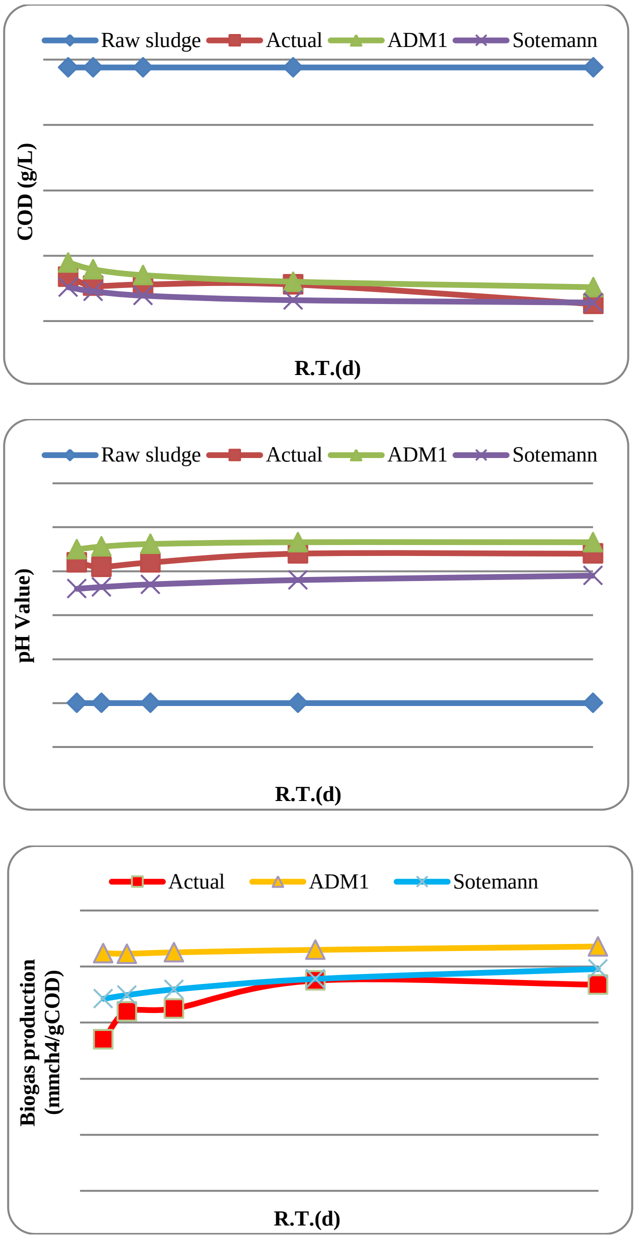

Fig.3 Actual and predicted (COD, pH value and Biogas production) for the digestion of primary sludge digestion.

The comparison of the actual and the two models predictions for effluent COD, pH value and gas production is summarized in Fig. 3. It can be seen that the model was able to predict the effluent COD, pH value and gas production with considerable accuracy. The actual effluent COD ranged between 10.30(g/L) and 12.40(g/L) while the COD predicted by the ADM1 ranged between 11.59(g/L) and 13.48(g/L), the COD predicted by the steady state model ranged between 10.42(g/L) and 11.58(g/L), the actual pH value ranged between 7.05 and 7.20, the predicted pH value by ADM1 ranged between 7.25 and 7.33 while the predicted pH value by the steady state model ranged between 6.80 and 6.95. The actual gas production ranged between 308 (L/d) and 350 (L/d), the gas production ADM1 prediction ranged between 369.11 (L/d) and 374.22 (L/d) while the gas production steady state model prediction ranged between 337.03 (L/d) and 358.23 (L/d)

3.2 *Mixture of primary sludge and trickling filter sludge digestion*

Izzett et al. (1992) operated two laboratory scale mesophilic (37 ^{0}C) anaerobic digesters fed a mixture of primary and humus (trickling filter) sludge from the Potsdam wastewater treatment plant (Milner ton, Cape, South Africa) at 7, 10, 12, 15 and 20 d retention time.

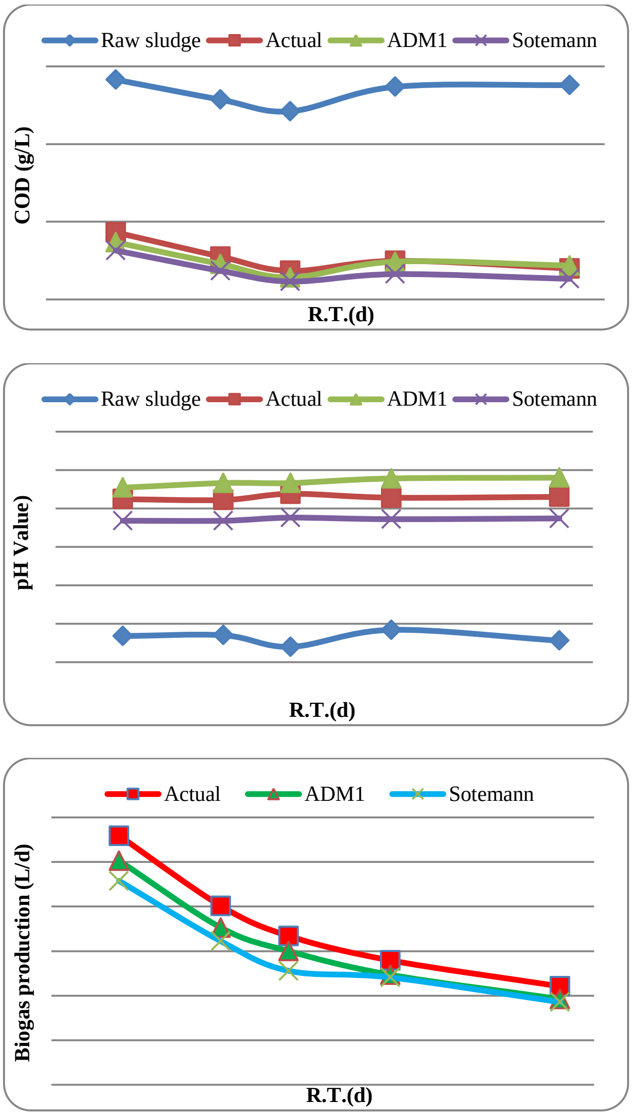

Fig.4 Actual and predicted (COD, pH value and Biogas production) for the digestion of mixture of primary and trickling filter sludge digestion.

The comparison of the actual and the two models predictions for effluent COD, pH value and gas production is summarized in Fig. 4. It can be seen that the model was able to predict the effluent COD, pH value and gas production with considerable accuracy.

The actual effluent COD ranged between 18.68(g/L) and 23.64(g/L) while the COD predicted by the ADM1 ranged between 17.85(g/L) and 22.37(g/L), the COD predicted by the steady state model ranged between 17.32(g/L) and 21.31(g/L), the actual pH value ranged between 7.11 and 7.19, the pH value ADM1 prediction ranged between 7.27 and 7.40 while the pH value steady state model prediction ranged between 6.84 and 6.88.The actual gas production ranged between 11.05(L) and 27.94(L), the gas production ADM1 prediction ranged between 9.62(L) and 25.14(L) while the gas production steady state model prediction ranged between 9.28(L) and 22.87(L).

3.2 *Mixture of primary and waste activated sludge digestion*

Ali A.M. (2013) studied the effect of mixing on the performance of mesophilic anaerobic digesters; the experimental set up consists of three similar pilot scale mesophilic anaerobic digesters have been designed and manufactured. Each has a cylindrical shape with a capacity of 0.24 m3. The digesters were fed with a mixture of primary and waste activated sewage sludge came out from a municipal wastewater treatment plant. The digesters were fed daily in a draw and fill manner, at a hydraulic retention time of 20 days by centrifugal pump. The operating temperature of the reactor is 35.5±0.5 ^{O}C.

The comparison of the actual and the two models predictions for effluent COD, pH value and gas production is summarized in Fig. 5. It can be seen that the model was able to predict the effluent COD, pH value and gas production with considerable accuracy. The actual effluent COD ranged between 32.85(g/L) and 40.20(g/L) while the COD predicted by the ADM1 ranged between 28.12(g/L) and 50.70(g/L), the COD predicted by the steady state model ranged between 29.62(g/L) and 49.97(g/L), the actual pH value ranged between 7.80 and 8.20, the pH value ADM1 prediction ranged between 7.48 and 7.58 while the pH value steady state model prediction ranged between 7.01 and 7.28. The actual gas production ranged between 90 (L/d) and 243.90 (L/d), the gas production ADM1 prediction ranged between 163.25 (L/d) and 316.00 (L/d) while the gas production steady state model prediction ranged between 121.02 (L/d) and 234.77 (L/d)

Conclusions

As evidenced by the results of the previous two examined models gave good results compared to the actual results of operations of the real anaerobic digestion of sludge of various kinds [primary sludge, mixture of primary sludge and waste activated sludge, and mixture of primary sludge and trickling filter sludge]. Because of the ease of use and application of the steady state model it's recommended to be used for the simulation and modeling of the anaerobic digestion of any type of sewage sludge –in case of steady state operation- because of its ease and its applicability.

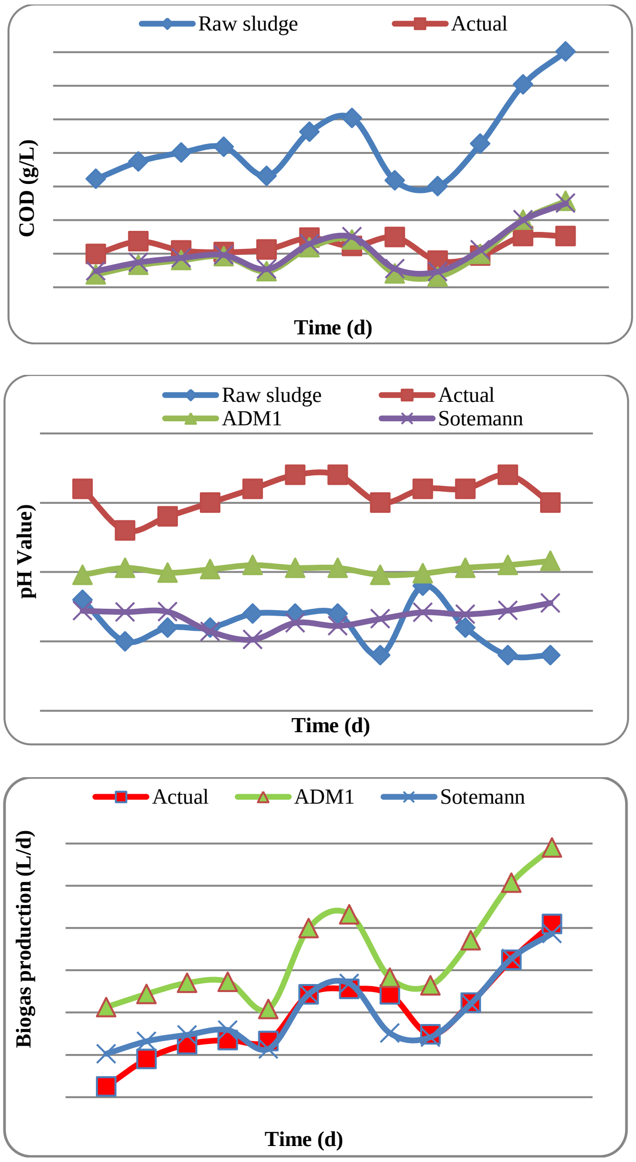

Fig.5 Actual and predicted (COD, pH value and Biogas production) for the digestion of mixture of primary and waste activated sludge digestion.

References

Aboulfotoh A. M. (Oct 2013) . ADM1 Simulation of the Mesophilic Anaerobic Digestion of Mixture of Primary and Secondary Sludge Treated by Effective Microorganisms , Vol.2 - Issue 10, *International Journal of Engineering Research & Technology (IJERT)*

Aboulfotoh A.M. (2012) Improvement of Anaerobic Digesters Using Pre-selected Microorganisms Ph.D. thesis, Zagazig University, Egypt.

Ali A.M. (2013) Performance optimization of sewage sludge anaerobic digestion using mathematical modeling Ph.D. thesis, Zagazig University, Egypt.

Batstone, D. J. (2006). Mathematical modeling of anaerobic reactors treating domestic wastewater: rational criteria for model use. Reviews in Environmental Science and Bio/Technology 5:57–71 , 5:57–71.

Elmitwalli, T., Sayed, S., Groendijk, L., van Lier, J., Zeeman, G., &Lettinga, G. (2003). Decentralized treatment of concentrated sewage at low temperature in a two-step anaerobic system: two up-flow hybrid septic tanks. Water Science and Technology ,48(6), 219-226.

Gujer, W.; Zehnder, A. J. B. (1983): Conversion Processes in Anaerobic Digestion. Water Science and Technology, Vol. 15, 127 – 167

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

Lawrence, A.W., (1971). Application of process kinetics to design of anaerobic processes. In: Gould, R.F. (Ed.), Anaerobic Biological Treatment Processes, Advances in Chemistry Series No. 105. American Chemical Society, Washington, DC.

Normak A.; Suurpere J.; Orupõld K.; JõgiE.andKokin E. (2012) Simulation of anaerobic digestion of cattle manure, Agronomy Research Biosystem Engineering Special Issue 1, 167-174.

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

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

Siegrist, H., Renngli, D., Gujer, W., 1993. Mathematical modeling of anaerobic mesophilic sewage sludge treatment. Water Sci. Technol. 27, 25–36

SötemannSw, MusvotoEv, WentzelMc And EkamaGa(2005a) Integrated chemical, physical and biological processes modeling Par t 1 - Anoxic-aerobic C and N removal in the activated sludge system. Water SA 31 (4) 529-544.

SötemannSw, Ristow Ne, WentzelMc, And EkamaGa (2005c) A steady state model for anaerobic digestion of sewage sludge. Water SA 31 (4) 511-528.

SötemannSw, Van Rensburg P, Ristow Ne, WentzelMc, Loewenthal Re AndEkamaGa(2005b) Integrated chemical, physical and biological processes modeling Part 2 - Anaerobic digestion of sewage sludge. Water SA 31 (4) 545-568.