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Extending the Applications of the ADM1 to Predict Performance of the Induced Bed Reactor (IBR) Co-Digesting Municipal Sludge with Bakery Waste

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Abstract

The goal of this research was to examine the stability of the induced bed reactor (IBR) digesting municipal sludge (MS) mixed with bakery waste (BW) by experiment and modeling. It was necessary to modify the Anaerobic Digestion Model number1(ADM1) to accurately predict the performance of the IBR for this mixed waste. The total mixed influent COD was 50 g/L with hydraulic retention times that varied from 27 to 6 days at mesophilic temperatures. The reactor reached the steady state at each HRT with no sign of inhibition or failure, however, the COD removal efficiency of the digester decreased from 92% to 72% with decreasing HRT. The modified ADM1 outputs agreed well with the measured stability indicators (pH, total volatile fatty acid (TVFA), Q (gas production), percent CH_4 at the longer retention times of 27, and 20 days. The model overestimated the pH, and methane percentage and underestimated the TVFA when the HRT was shorter (12, 9 and 6 days). However, the model predicted well the trends of the observed data and the overall stability process of the digester until 6 d HRT. This research provided an alternative for the disposal of industrial bakery waste and also pointed out the ability of the IBR to manage high waste loads stably, while providing high energy production.

Keywords: ADM1, Anaerobic Digestion, bakery waste, energy recovery IBR, municipal sludge, stability

1. Introduction

Treating and reducing industrial waste pollution is a major challenge for engineers and scientists because industrial waste may have a significant negative effect on the environment and treatment of industrial waste is expensive. Treatment of organic industrial waste anaerobically may stabilize the waste and produce biogas as a byproduct of the process. Several studies have demonstrated the benefits of anaerobic treatment of food waste ((Bouallagui et al. 2003; Kabouris et al. 2009; Zhang et al. 2007). However, the following operational problems were reported during the anaerobic process: 1) low solubility of the food waste prevented it from being easily biodegradable by the microorganisms, 2) cost of grinding and mixing of the waste so it could be pumped easily to the digester, 3) toxicity and inhibition of the anaerobic microorganisms due to the accumulation of total volatile fatty acids (TVFA) produced when long chain fatty acids, amino acids and monosaccharaides are broken down, 4) toxicity from ammonia nitrogen due to the presence of degradable proteins, and 5) presence of excessive ions such as $Mg^{2+,}$ Ca^{2+}, Na^{+} that can affect the stability of the process (Alves et al. 2001; Angelidaki and Ahring 1993; Chen et al. 2008; Demitry 2016; Kroeker et al. 1979; Lalman and Bagley 2001; Pereira et al. 2005; Salminen et al. 2000; Yenigün and Demirel 2013).

Generally, municipal wastewater reclamation facilities use anaerobic digestion to stabilize sludge and use the methane produced as a source of energy. The US Environmental Protection Agency (EPA) estimates in 2012 that more than 181.4 million metric tons of raw domestic wastewater are produced in the United States daily (Effluents and Consumption 1996; EPA 2012). In 2016, the amount of municipal sludge is expected to reach 200 million metric tons with the increase of about 10% in the US population.

A hypothesis of this study is that sewage sludge can be anaerobically co-digested with food waste to produce energy and reduce the amount of the wastes at the same time if carefully operated.

The bakery industry is a major food industry around the world that produces a significant amount of waste daily; bakery waste (BW) is a good candidate to be co-digested with municipal sludge (MS) since it contains high organic matter (carbohydrates and lipids) but minor amounts of protein. There are two kinds of BW the first is waste collected from the pan wash of the bakery industry (cookies, muffins, and pies). The co-digestion of this kind of waste was discussed in detail in our previous studies (Demitry et al. 2015). The second type of BW comes from product residuals or from the process of removing the waste when switching from one product to another.

In this study, the second kind of BW was examined. Digesting the BW alone will likely fail due to its characteristics, having low pH (~4), high concentrations of (TVFA, ~0.45 g/L), and the lack of proteins. However, the co-digestion of BW with other organic wastes containing proteins and alkalinity such as MS will provide the required nutrients and lead to effective anaerobic co-digestion (Neves et al. 2009; Zhang et al. 2011; Zhang et al. 2007).

The Anaerobic Digestion Model Number1 (ADM1), developed for predicting the dynamic behavior of municipal sludge digestion (Batstone et al. 2002) was used in this study to predict performance of the co-digestion of BW and MS using the Induced Bed Reactor (IBR) anaerobic digester (Dustin 2010; Hansen and Hansen 2005). The input constituents to the model are the chemical oxygen demand (COD) for carbohydrates, proteins, and lipids, the physical characteristics (retention time, liquid and gas volume) for the digester and the temperature. This model has been used extensively for MS systems for predicting process efficiency. The use of the model here will be slightly different than the original intent: to predict the digester's stability indicators (pH, TVFA (mg/L), gas flow rate Q (m^3/d), and methane content by volume)). The ADM1 models biochemical reactions inside an anaerobic bioreactor and thus can help predict response of the reactor under different operating conditions. However, the model required modification to extend its application to cover co-digestion of MS and BW because the characteristics of the new substrate are different from MS alone. An ADM1 model modified for BW and MS will predict stability indicators that will help with full scale plant design and thus assist in the transfer of this technology from research to practice.

Objectives:

The objectives of this research were twofold:

(1) Examine the stability of the Induced Bed Reactor (IBR) in the case of anaerobic co-digestion of MS mixed with BW

(2) Develop and modify the ADM1 to accurately predict the co-digestion of BW and MS.

ADM1 background

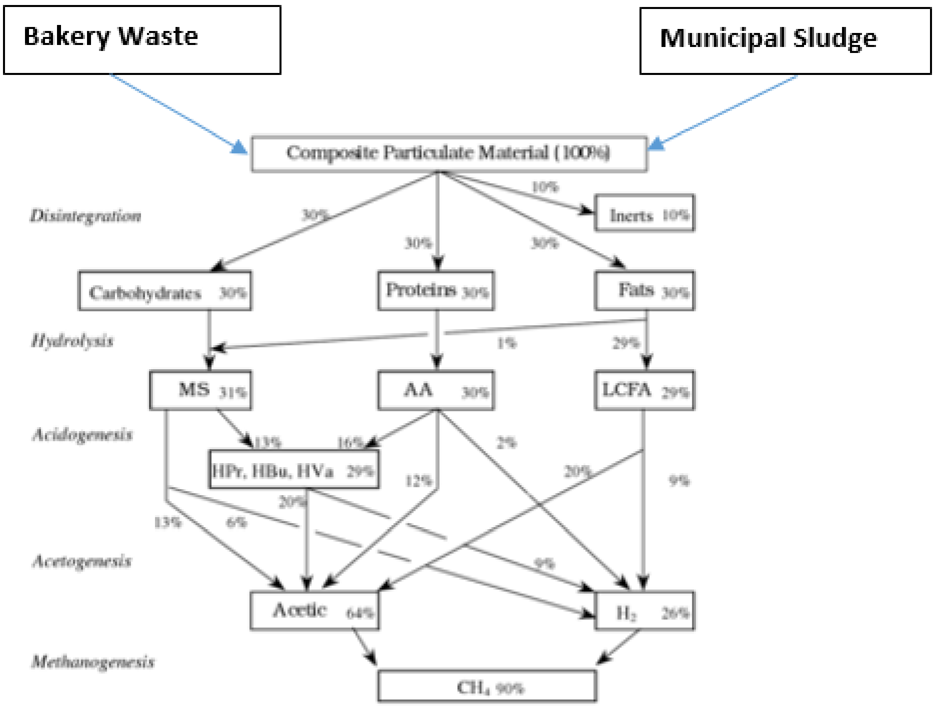


Figure 1. The ADM1 structure (Batstone et al. 2002)

The ADM1 was developed by an IWA group in 2002 (Batstone et al. 2002). The ADM1 is a mathematical structured model that is often used as a framework model that investigators can modify and choose coefficients according to specific substrates and digester configuration. The model consists of a set of 32 differential equations for modeling the rates of change of the different constituents in the liquid and gas phases as follows: 10 for soluble matter degradation, 2 for inorganic carbon and inorganic nitrogen, 4 for particulate matter, 8 for biomass concentrations, 2 for cations and anions and an additional 6 for acid-base reactions (Batstone et al. 2002). The original model includes coefficients and parameters for specific types of organic matter. The model equations are based on a continuous stirred-tank reactor (CSTR) system (Batstone et al. 2002). In order to use the model for different wastes and reactors, modification, optimization, and validation are required (Batstone et al. 2002).

The model simulates the process of anaerobic digestion in four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 1).

There are two types of methanogenesis, one uses hydrogen gas (H_2) as a substrate, and the other uses acetic acid as shown in Figure 2 (Demirel 2014). One of the original model's assumptions is that the majority of methane produced in an anaerobic digester is by acetoclastic methanogenesis or degradation of acetic acid to methane rather than hydrogenotrophic methanogenesis; production of methane from hydrogen (Batstone et al. 2002). The ratio between the two pathways respectively was assumed in the ADM1 model to be 64:26 based on COD (Figure 1), while 10% of the COD was assumed as non-biodegradable organic matter . This statement agrees with previous studies regarding the major role of acetoclastic methanogenesis for the formation of methane in the process of anaerobic digestion of sewage sludge (McCarty 1964; Metcalf et al. 2013; Smith and Mah 1966). While the previous studies demonstrated the role of acetoclastic methanogenesis for methane formation from sewage sludge, Traversi et al, (2011) concluded that methanogen type and diversity is dependent on the feed characteristics and process conditions (Traversi et al. 2011). Based on the conclusion of Traversi et al, in (2011), either kind of methanogenesis (hydrogenotrophic or acetoclastic) may have the major role for methane formation during anaerobic digestion. However, despite the increasing attention on anaerobic digestion of biomass for production of methane, there is relatively little information specifically about the activity and the performance of both acetoclastic methanogenesis and hydrogenotrophic methanogenesis (Demirel and Scherer 2008) in various situations.

Differences in the digester's operation and substrates affect the behavior of each group of methanogens. Therefore, the change in the IBR's environment due to adding BW to the system and the changes in the HRT from 27 to 6 days, enhanced the production of biogas through the increase of hydrogenotrophic rather than acetoclastic methanogenesis. This assumption was based on other research that demonstrated the role of hydrogen gas in methane formation and demonstrated that hydrogenotrophic methanogens were the dominant population (Demirel 2014; Demirel and Scherer 2008; Schmidt et al. 2000). Moreover, Padmasiri et al. (2007) reported that the levels of hydrogenotrophic methanogens increased during decreased reactor performance (Padmasiri et al. 2007).Other researchers reported significant impacts of the OLR, HRT and temperature on a decrease of acitoclastic methanogenesis in the system and a dramatic increase in TVFA concentrations (Blume et al. 2010; Krakat et al. 2010; Krakat et al. 2011). Figure 2 shows the anaerobic digestion process as described by Demirel et al, 2014.

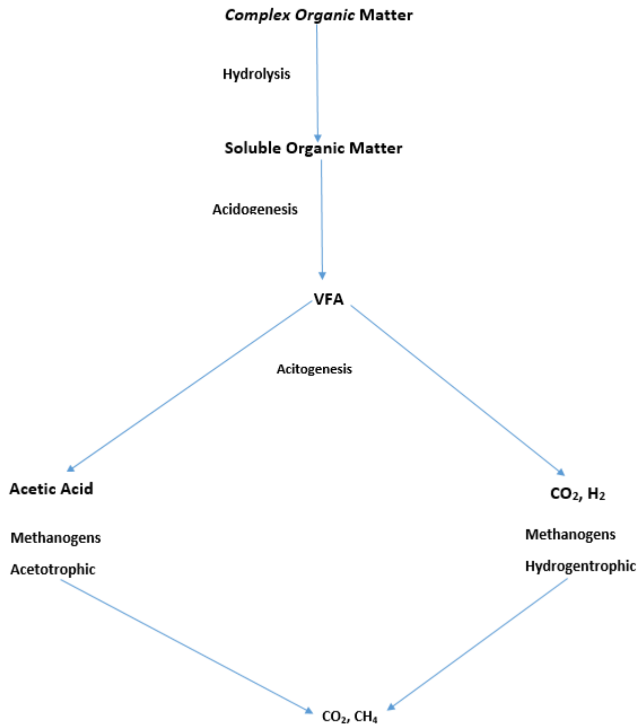


Figure 2. The stage of anaerobic digestion process adapted from (Demirel 2014)

Suggested modification for the ADM1

The modification to the model was made by changing the ratios between acetic acid and hydrogen gas production. These changes were made to reflect the assumption that in the case of MS mixed with BW, more methane was produced through H_2 (hydrogenotrophic methanogenesis) than acetic acid (acetoclastic methanogenesis). However, the changes in the ratios between acetic and hydrogen were made by trial and error until the model predicted the process stability best under different HRT's. The ratio between H_2: acetic acid in the modified model is 48%:42%, respectively. The change in the ratio is shown in the following equations:

The original equations in the ADM1 ((Batstone et al. 2002):

$$\frac{dac}{dt} = \tau\left(S_{ac,in} - S_{ac}\right) + ((1 - Y_{su})F_{ac,su}P_5 + (1 - Y_{aa})F_{ac,aa}P_6 + 0.7\left(1 - Y_{fa}\right)P_7 + 0.31(1 - Y_{c4})P_8 + 0.80(1 - Y_{c4})P_9 + 0.57\left(1 - Y_{pr}\right)P_{10} - P_{11} \quad (1)$$

$$\frac{dh_2}{dt} = \tau\left(Sh_{2,in} - dSh_2\right) + ((1 - Y_{su})F_{h2,su}P_5 + (1 - Y_{aa})Fh_{2,aa}P6 + 0.30\left(1 - Y_{fa}\right)P_7 + 0.15(1 - Y_{C4})P_8 + 0.20(1 - Y_{c4})P_9 + 0.43\left(1 - Y_{pro}\right)P10 - P_{12} - P_t \quad (2)$$

The modified equations:

$$\frac{dac}{dt} = \tau\left(S_{ac,in} - S_{ac}\right) + \Big((1 - Y_{su})F_{ac\_su}P_5 + (1 - Y_{aa})F_{ac\_aa}P_6 + 0.5\left(1 - Y_{fa}\right)P_7 + 0.2(1 - Y_{c4})P_8 + 0.4(1 - Y_{c4})P_9 + 0.50\left(1 - Y_{pro}\right)P_{10} - P_{11}\Big) \quad (3)$$

$$\frac{dh_2}{dt} = \tau\left(Sh_{2,in} - Sh_2\right) + (1 - Y_{su})Fh_{2-su}P_5 + (1 - Y_{aa})Fh_{2-aa}P_6 + 0.5\left(1 - Y_{fa}\right)P_7 + 0.26(1 - Y_{C4})P_8 + 0.6(1 - Y_{C4})P_9 + 0.50\left(1 - Y_{pro}\right)P_{10} - P_{12} - P_t \quad (4)$$

where Sac = soluble component for acetic acid (kg COD m^{-3}), Sh_2= soluble component for hydrogen gas (kg COD m^{-3}), Ysu= yield of biomass on carbohydrates, Yaa=yield of biomass on amino acids, Yfa =yield of biomass on long chain fatty acids, Ysu=yield of biomass on butyric acid, Ypro= yield of biomass on propionic acid, Fac_aa= yield of acetic acid from amino acid, Fh_2_aa=yield of hydrogen gas from amino acid, Pi= Processi , Q/Vliq (d^{-1}), Q=flow rate (m^3/d), Vliq=liquid volume of the digester (m^3), Pt=transfer rate of hydrogen gas.

In addition, some of the kinetic parameters of the model were changed using trial and error to improve the model prediction to reflect the co-digestion situation of MS and BW (Table 1):

Table 1. Kinetic coefficients for modified ADM1 model

Parameters	Name	Unit	Initial Values	Estimated Values
K dis	Disintegration Constant	Day $^{-1}$	0.4	0.5
K hydr Ch	Carbohydrates hydrolysis constant	Day $^{-1}$	0.25	13
K hyd Pr	Proteins hydrolysis constant	Day $^{-1}$	0.2	10
K hyd Lip	Lipids hydrolysis constant	Day $^{-1}$	0.1	10.5

The initial values were obtained from (Batstone et al. 2002)

The estimated values for Municipal sludge mixed with Bakery Waste

2. Materials and Methods

The stability indicator parameters (pH, TVFA, gas flow, and methane content) were monitored in order to examine the stability of the IBR treating MS and BW. The experimental work was done using a pilot scale IBR developed at Utah State University to apply high-rate anaerobic digestion techniques to high solids content substrate (Hansen and Hansen 2005). The IBR total volume was 60 liters, with liquid volume of 54 liters and gas volume of 6 liters. In this study, the IBR was operated under mesophilic temperature (40°C). Figure 3 shows the cross section of the IBR.

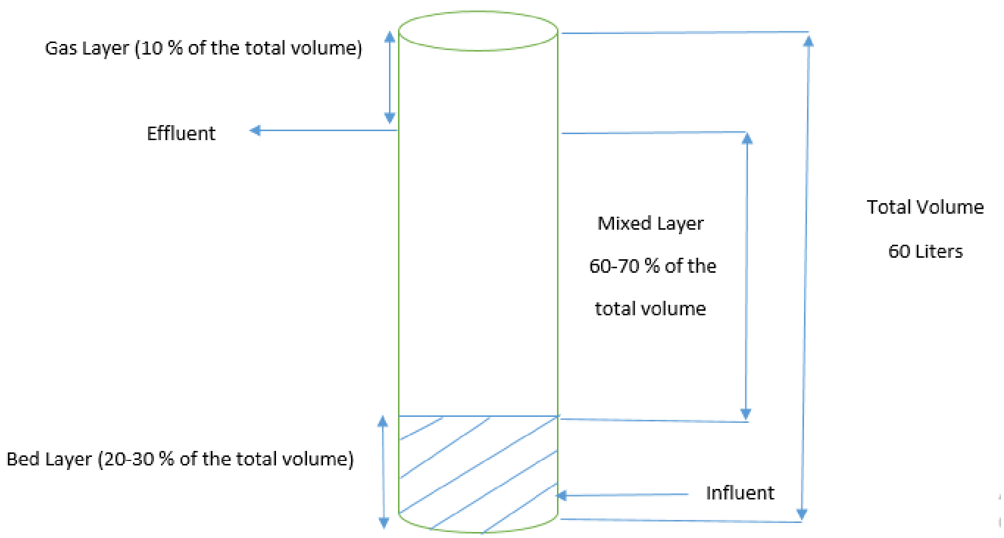


Figure 3. IBR cross-section

The municipal sludge used in the IBR was obtained from Central Weber Sewer Improvement district, Ogden, UT; the BW was obtained from CSM Bakery Products, Ogden, UT. The MS and BW were collected in the period of August, 2015 to February 2016. The BW and MS were mixed based on COD; the ratio was 50:50% MS:BW. The IBR was fed with the mixed solution at various retention times/organic loading rates. The hydraulic retention times (HRT) in this research, were, 27, 20, 18, 12, 9 and 6 days respectively. The mixed solution was fed to the reactor 6 times per day using automated system (Omron industrial automation H3CR-F, Kyoto, Japan).

Samples were collected from the effluent side of the IBR, pH was measured with an Oakton Vernon Hills,(IL USA) meter and TVFA measured using HACH method 8196(HACH 2014). Ammonia nitrogen was measured using HACH method 10031(HACH 2015). The lab temperature was 24°C; the biogas was collected and the volume was measured using Tedlar gas bags (CEL scientific corporation, Cerritos, CA, USA). The volume of the measured gas at the Food Engineering Laboratory was corrected to an equivalent volume of 1 atm pressure using equation 8:

$$P_1V_1 = P_2V_2 \qquad \text{...(5)}$$

Where:

P1 = The average atmospheric pressure at the lab (0.86 atm)

V1 = The measured volume of the gas(m^3)

P 2 = The atmospheric pressure (1.0 atm)

V2 = Corrected gas volume (m^3)

The correction was done because the ADM1 assumed the atmospheric pressure is 1 atm, while the average atmospheric pressure at Logan, UT, USA is 0.86 atm.

Methane and carbon dioxide content of the gas were measured using an Agilent 6890 GC, RT-M sieve 5A Plot capillary column (Restek) (Agilent, Santa Clara, CA).

Digester influent TCOD of the mixed and diluted (tap water) waste was 50 ± 1.17 g/L; the ratio between the BW:MS was 50:50 based on COD. The IBR was operated at mesophilic temperature (40 °C).

All the above mentioned parameters were measured in duplicate or triplicate and quality control protocols were applied for the analytical instruments calibrations. Data were recorded in spreadsheets and R database structures for analysis. Table 2 shows characteristics of the MS and BW.

Table 2. Municipal sludge and bakery waste characteristics

Parameter	Units	Municipal Sludge (MS)	Bakery Waste (BW)
pH		6.98 ± 0.21	4.00 ± 0.28
TS	%	5.15 ± 0.34	9.35 ± 0.22
VS	% of TS	91 ± 2.3	96 ± 0.65
COD	g/L	76 ± 8.16	175 ± 13.64
Alkalinity ($CaCO_3$)	mg/L	4150 ±156	BDL(<20mg/L)
TKN	mg/L	2118 ± 89	BDL(<50 mg/L)
NH3	mg/L	1100 ± 104	BDL(<0.8mg/L)

Each point is the average of triplicates. ± shows standard deviations among replicates.
BDL= Below Detection Limits.

The IBR stability and performance were evaluated with organic loading rates ranging from relatively low (~1.9 kg COD m^{-3} d^{-1}) at a 27 d HRT to high (~8.5 kg COD m^{-3} d^{-1}) at a 6 d HRT. The work in this study was done using the six different retention times shown in Table 3.

The decision to switch from one HRT to another was based on whether the IBR performance reached stable steady-state situations, assumed to be occurring when digesters were operating at or near their recommended levels for the stability indicators (pH ~7, TVFA <2000 mg/L, NH_3 <1500 mg/L) and when gas production and gas rates were relatively constant (±10% per day)) (Kroeker et al. 1979).

Table 3. Experimental phases, daily digester feed, the HRT, the OLR, and the rate of methane produced per COD converted

Phase	Feed Q (L/d)	Retention Time (HRT, d)	OLR (Kg COD $m^{-3}d^{-1}$)	Rate of methane production $(\frac{L\ CH_4}{g\ COD})$
1	2	27	1.85	0.42
2	2.7	20	2.48	0.44
3	3	18	2.78	0.42
4	4.5	12	4.15	0.42
5	6	9	5.56	0.42
6	9	6	8.33	0.35

ADM1 Model

The ADM1 equations in this study were coded and implemented using R programming software for statistical computing (Team 2015). R was chosen among several options because of its statistical and graphics capability. The differential equations were coded as R functions and integrated using the LSODE method from the deSolve library (Soetaert et al. 2010).

3. Results and Discussion

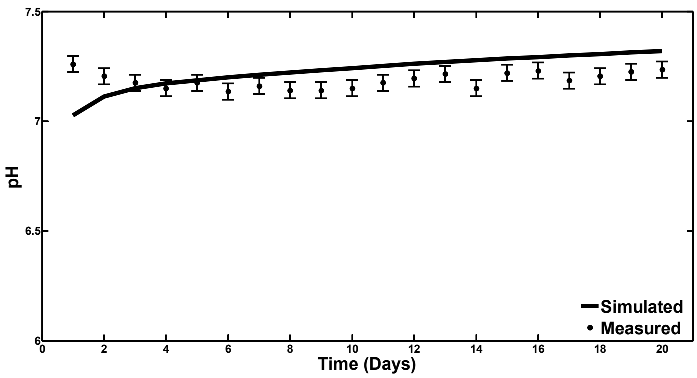
The original ADM1 model was used to simulate performance at the longer HRTs and was unable to predict the stability indicators (pH, TVFA (mg/L), Q (m^3/d), and CH_4 %) and overall stability for MS mixed with BW (COD=50 g/L; different HRT's, and temperature = 40°C). The original model did not include the necessary kinetic coefficients (Table 1) required to predict stability parameters for the case of co-digestion of MS and BW. Accordingly, modifications to the ADM1 model were required in order to extend the ADM1 application to the case of the mixed waste in this study.

The ADM1 was modified based on recent studies reporting hydrogenotrophic methanogenesis for methane production favored over acetoclastic methanogenesis as described by Equations 1-4.

Figures 4 -7 show the results for phases 1, 2, 4, and 6 respectively of the experiment using the modified model, in which each observation represents the average of duplicate samples.

Results for phase 1 (HRT = 27 days) are shown in Figure 4. The modified model outputs agree well with the observations in case of pH, TVFA (mg/L) and gas flow (m^3/d), while acceptably in predicting the measured methane percentage (the difference between simulated and measured =±10 %). Moreover, the model outputs and the observations have the same trends (from days 2-20). The fluctuations in the measured stability indicators during the process were very small. Relatively high methane percentage (70.65 ± 1.45%) was observed at a COD removal efficiency of 92 ± 0.67%. The effluent NH_3 = 345 ± 14.2 mg/L, and TVFA concentration remained below 100 mg/L, all signs of stable operation.

Phase1:



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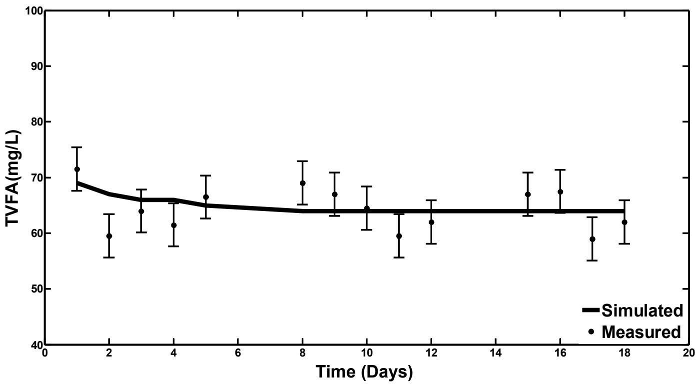

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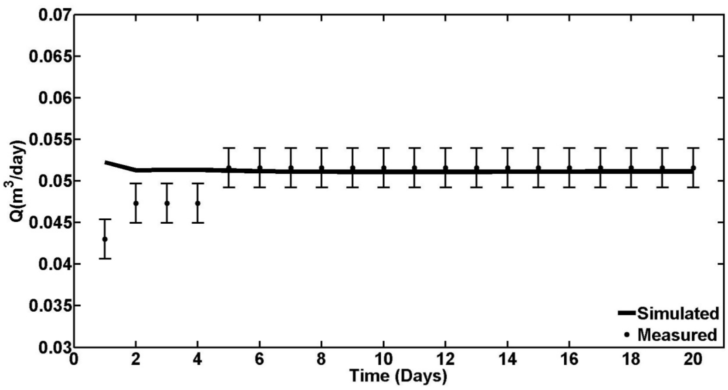

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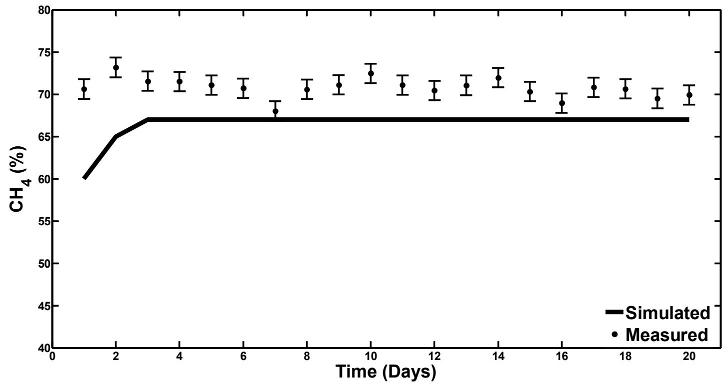
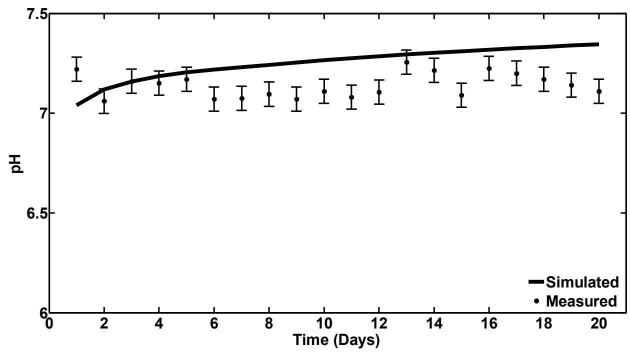


d

Figure 4. Comparison between simulated and measured data, a=pH, b=TVFA (mg/L), c=Q(m^3/d) and d=CH_4 %, the error bars represents the standard deviation phase 1

In this Phase the IBR was under stable steady state conditions since the reactor was operating at or near the recommended levels for effective digesters, pH= 7.5-6.5, TVFA ≤ 2000 mg/L, propionic acid ≤ 900 mg/L, ammonia NH_3 ≤ 1500 mg/L (Bitton 2005; McCarty 1964; Metcalf et al. 2013; Wang et al. 2009), and there was stable biogas production and CH_4 percentage (±10 % per day). However a high methane percentage content in the biogas, in the range of 65 - 75%, reflects a healthy digester (Kroeker et al. 1979; Turovskiy and Mathai 2006). The rate of methane production per COD removed was 0.42 L CH_4/g COD during phase 1

Phase 2



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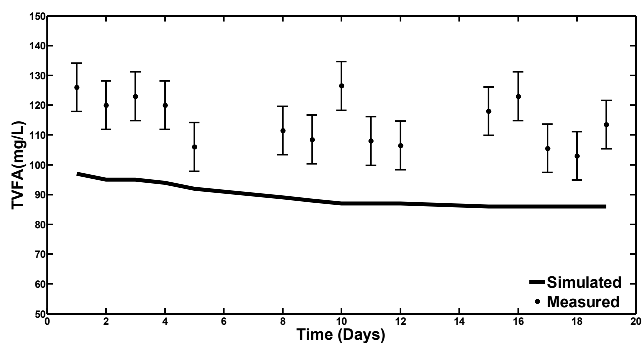

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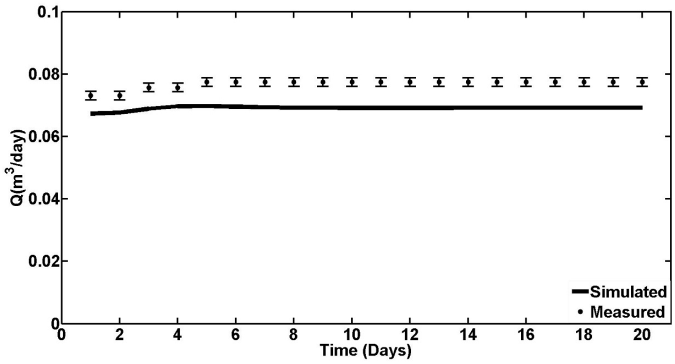

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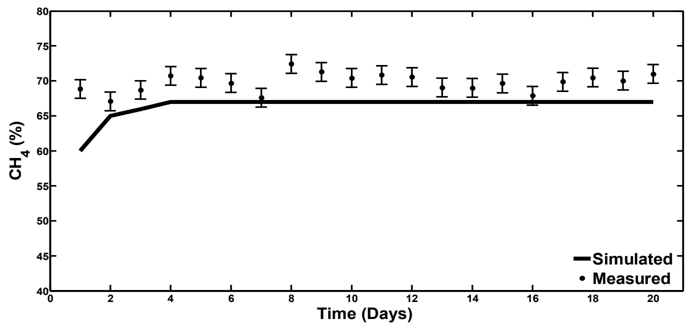

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Figure 5. Comparison between simulated and measured data, a=pH, b=TVFA (mg/L), c=Q(m^3/d), d=CH_4%= the error bars represents the standard deviation- Phase 2

Results for phase 2 (HRT= 20 days) are shown in Figures 5. The modified model reasonably predicted the pH, gas flow(m^3/d) and methane percentage (%), while underestimating the TVFA (mg/L). The simulation and the observations have the same trends (Day 4-Day 20) as shown in Figure 5. There were no fluctuations in the observations: the IBR was run under steady- state and effective performance conditions. The COD removal was 90 ± 1.4 % and the average effluent NH_3 was 358 ± 17.8 mg/L, similar to Phase 1. The increase in the OLR from 1.85 Kg COD m^{-3} d^{-1} in Phase 1 to 2.48 Kg COD m^{-3} d^{-1} in Phase 2 did not affect the digester performance, both the model outputs and the observations show effective digester performance and no inhibition or stress was detected in Phase 2. The rate of methane production per COD removed was 0.44 L CH_4/g COD during phase 2, which was slightly higher than phase 1 (0.42 L CH_4/g COD).

In phase 3 (HRT= 18 days), the digester performance was stable, the pH values were close to phase 2. Slightly increase in the TVFA (mg/L) accumulation and in the gas production (m^3/d) were noticed compared to phase 2. Despite the increase in the TVFA, there were no inhibition or stress detected during phase 3. Because the IBR was under steady state conditions, the decision was taken to increase the OLR to reach 4.15 kg COD $m^{-3}d^{-1}$ as shown in phase 4. The rate of methane production per COD removed was 0.42 L CH4/g COD during phase 3, which demonstrated the stable and effective performance of the IBR since the rate of methane production was stable during phase 1- 3.

Phase 4:

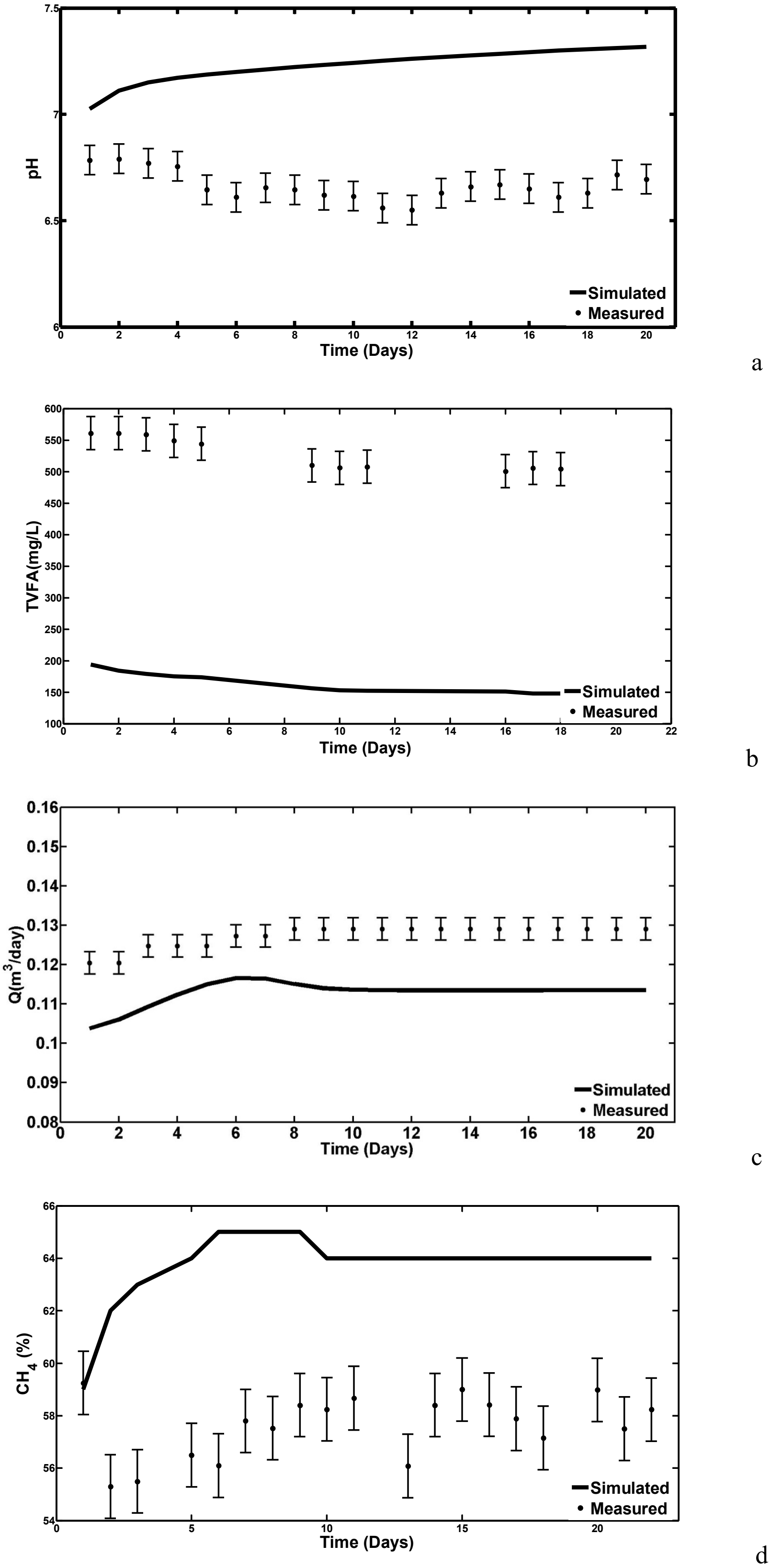
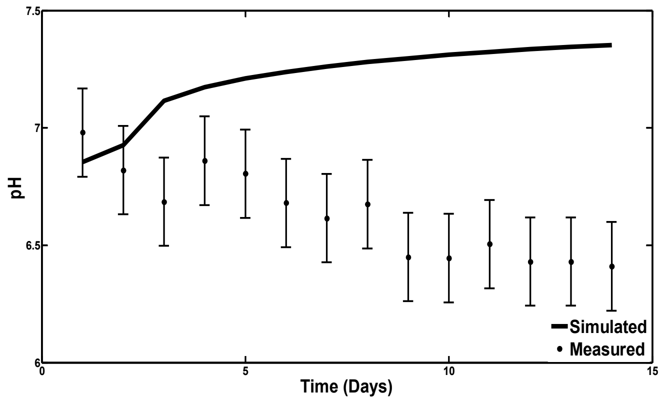


Figure 6. Comparison between simulated and measured data, a=pH, b=TVFA (mg/L, Q= (m^3/d), d=CH_4%, the error bars represents the standard deviation phase 4

In Phase 4 (HRT=12 days) as shown in Figure 6, the digester performance went down when the OLR was increased to 4.15 kg COD m^{-3} d^{-1}. A dramatic increase in the observed TVFA was seen, along with the drop in the observed pH (6.7-6.9). However, despite the increase in the measured TVFA and the drop in pH values, stable performance was achieved and the digester produced significant amounts of biogas (0.15 m^3/d) and a stable percentage of CH_4 (59%) at this shorter HRT. This demonstrated the stability of the process in Phase 4 since process instability is usually indicated by rapid increases in the TVFA and decrease in the methane production (Kroeker et al. 1979). Moreover, stable methane production per COD removed from the IBR was noticed (0.42 L CH_4/g COD) as shown in Table 3.

In Phase 4 the model outputs did not agree with the observations (Figure 6). The model overestimated the pH, underestimated the TVFA (mg/L), while it reasonably predicted the gas flow (m^3/d) from the IBR and overestimated the methane percentage. Even though the model did not predict the stability indicators in Phase 4, it was still able to predict the digester's trends and the overall process stability reflecting an active digester performance.

Phase 6:



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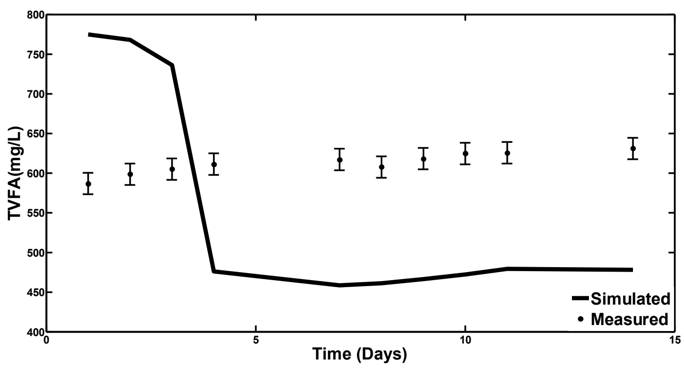

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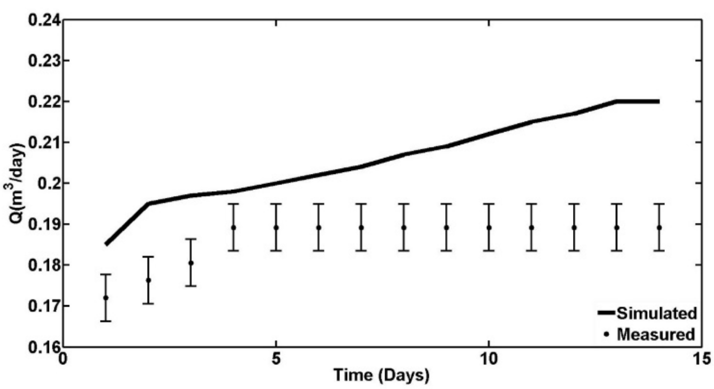

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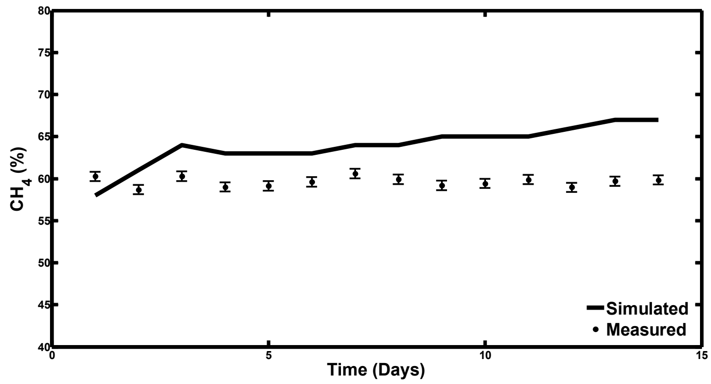

d

Figure 7. Comparison between simulated and measured values, a=pH, b=TVFA (mg/L, Q= (m^3/d), d=CH_4%, the error bars represents the standard deviation phase 6

In Phase 6, at an HRT of 6 days (Figure 7), the digester was still effective and stable. The observations show an increase in TVFA to ~611 mg/L compared to previous phases, and a drop in the measured pH values (to ~6.7), but at the same time shows an increase in the gas production (~0.19 m^3/day). Stability parameters indicated a stable steady state of the IBR in Phase 6. However, a decrease in the rate of methane production from the IBR per COD removed was noticed in Phase 6 (0.35 L CH_4/g COD). The reduction of the methane production rate in Phase 6 may be an indicator of a partial stress in the system.

On the other hand, the model overestimated the pH (by +12%), while underestimated the TVFA (by 20%). The model predicts acceptably (+10%) the gas flow (m^3/d) and methane percentage (%) in the first 10 days, and overestimated them in day 11 - day 15 as shown in Figure 7. However, the model successfully predicted the general trend of the IBR and the stability situation in Phase 6. At any rate, the differential equations of the model are non-linear and it is complicated to optimize all the model's coefficient to predict well the process of the anaerobic digestion. Several studies have reported disagreement between the model and the observed data for continuous and semi continuous stirred reactors ((Fezzani and Cheikh 2008; Parker 2005; Razaviarani and Buchanan 2015; Shang et al. 2005).

In this study, the main reason for the disagreement between the model outputs (simulated) and the observed data from the IBR in low HRT (≤12 days) is because the ADM1 model considered that the digester is a single stirred tank reactor (Batstone et al. 2002) not an IBR, which behaves more like 2 tank reactors in series (Figure 3), with the first having a high biomass concentration and the second a low biomass concentration. Accordingly, the ADM1 needs more modifications to predict the IBR performance especially when the HRT ≤12 days by considering mass balances separately for the two different reactors.

These results demonstrated the effective performance of the IBR and its ability for handling high OLR (8.33 kg COD $m^{-3}d^{-1}$) of mixed organic matter. This stable performance at low HRT is characteristic of the IBR since the bed of the reactor retains the microbes in the bottom 20-30% of the tank (Figure 3), and helps to prevent the system from being stressed until the digester adapts to the substrate leading to reactor stability (Dustin 2010; Hansen and Hansen 2005).

The co-digestion of MS mixed with BW is cost-effective for energy recovery. There was a considerable increase in the biogas and methane percentage in the presence of bakery waste. No chemical buffer (NaOH or Na_2CO_3) was required during the process to buffer the pH as the MS provided adequate buffering for the system to keep the pH in the recommended ranges (6.5-7.5). Also, the BW characteristics avoided most of the problems related to the digestion of food waste as mentioned in the literature since the BW doesn't required any grinding like more typical food waste from restaurants, fruits waste and core waste, moreover, the BW is highly soluble when mixed with MS which helps the microorganisms to utilize it quickly.

The digester was stable during all the phases but the efficiency of the IBR removing organic matter was affected as the loading rate increased and the residence time decreased (Figure 37). In Phase 1 (HRT = 27 days, OLR = 1.85 kg COD $m^{-3}d^{-1}$) the IBR successfully removed 92% (as COD) of the initial organic matter and the methane was relatively high (72%). In Phase 4 (HRT = 12 days, OLR = 4.15 kg COD $m^{-3}d^{-1}$) the efficiency decreased to reach 82% and CH_4 content dropped to 58% while in Phase 6 (HRT = 6 days, OLR = 8.33 Kg COD $m^{-3}d^{-1}$) the organic matter removal efficiency dropped to 72% and the CH_4 was still at the range of 58% of the biogas (Figure 8).

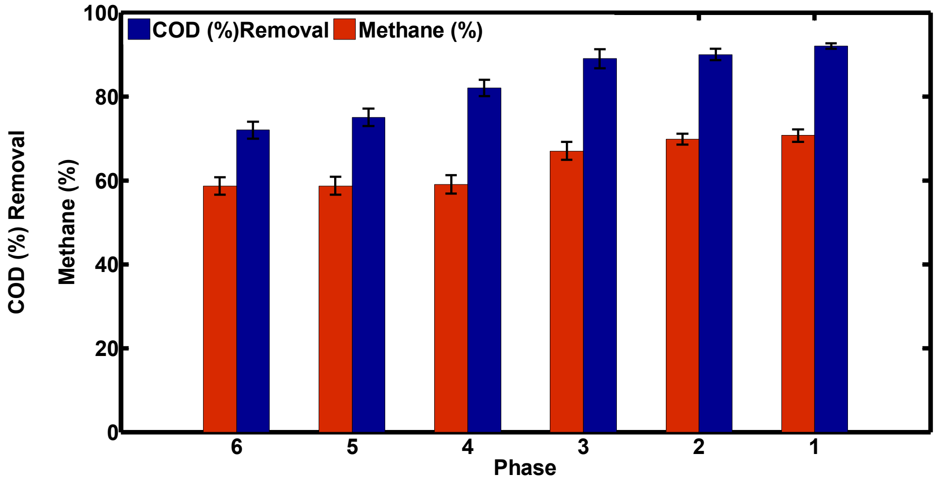

Figure 8. The relation between steady state % removal of COD, percentage methane content and HRT- IBR

4. Conclusion

The Induced Bed Reactor (IBR) was evaluated for co-digesting MS and bakery waste BW at a 50%:50% ratio of MS: BW based on COD. Highly stable performance for the IBR was achieved over a broad range of retention times of (27, 20, 18, 12, 9 and 6 days). The IBR remained stable at all HRTs though the TVFA did increase significantly when the HRT dropped below 10 days. Stable methane production per COD removed (0.42 L CH_4/g COD) was reported in Phase 1 through Phase 5, while a reduction of methane production rate (0.35 L CH_4/g COD) was noticed in Phase 6. All these results confirm that BW and MS provide the nutrient balance for the IBR's microorganisms. Also, these results pointed out the ability of the IBR to handle high COD loading with relatively short HRT for this mixed substrate.

The ADM1 model was modified to more accurately predict the co-digestion of BW and MS by IBR. The modification increased the model's ability to predict the stability indicators of the digester in all phases. The modified model was accurate and agreed reasonably well with the measured stability indicators (pH, TVFA (mg/L), Q (m^3/d) and methane content by volume (%)) especially with 27, 20 and 18 HRT. The modified model couldn't predict accurately the stability parameters with shorter HRT since the IBR acts as two different reactors (bed and mixed reactors).

This research shows potential for anaerobic digestion of bakery waste management and its role for energy recovery for treatment plants. It also demonstrated the benefits of the modified ADM1 model as a useful tool to support decision making for anaerobic digestion of BW and MS.

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