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THE ENHANCED ANAEROBIC DEGRADABILITY AND KINETIC PARAMETERS OF PATHOGENIC INACTIVATION OF WASTEWATER SLUDGE USING PRE- AND POST-THERMAL TREATMENTS PART 2.

MEJORAMIENTO DE LA DEGRADABILIDAD ANAEROBIA Y PARÁMETROS CINÉTICOS DE LA INACTIVACIÓN DE PATÓGENOS DE LODOS RESIDUALES USANDO PRE- Y POST TRATAMIENTO TÉRMICO PARTE 2.

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Abstract

In Mexico, wastewater sludge is characterized by high concentrations of organic compounds and pathogenic microorganisms. This study proposes the development and comparison of the anaerobic digestion enhanced with thermal pre-treatment denominated Pre-anaerobic digestion (Pre-AD) and with thermal post-treatment denominated Post-anaerobic digestion (Post-AD) processes for treating wastewater sludge. Additionally, the results from a kinetic model that was developed for thermal inactivation were used to describe the inactivation of faecal coliforms, *Salmonella* spp. and helminth ova during the thermal treatment stages. In the Post-AD operational batch test, it was determined that a period of 27 d was necessary to reduce the volatile solids (VS) by 38% at an organic loading rate of 0.65 kg VS $m^{-3}d^{-1}$. When the Pre-AD process was evaluated, 13 d of treatment was sufficient for meeting the stabilisation criteria at an organic loading rate (ORL) of 1.25 kg VS $m^{-3}d^{-1}$ in the batch test. In a semicontinuous operation tests, the Pre-AD process could be operated at an OLR of 3 kg VS $m^{-3}d^{-1}$, while the Post-AD process could only be operated at an OLR of 1.5 kg VS $m^{-3}d^{-1}$. The bacteria and helminth ova were inactivated at 70°C for 1 h and 80°C for 2 h, respectively.

Keywords: anaerobic-thermal sludge digestion, thermal inactivation, thermal-anaerobic sludge digestion, pathogenic thermal inactivation, kinetic parameters.

Resumen

En México, los lodos residuales son caracterizados por altas concentraciones de compuestos orgánicos y microorganismos patógenos. El presente estudio propone el desarrollo y comparación del proceso de digestión anaerobia mejorada con un pre-tratamiento térmico denominada Pre-AD y con un post-tratamiento térmico denominada Post-AD para el tratamiento de lodos residuales. Adicionalmente, son mostrados los coeficientes cinéticos de un modelo matemático desarrollado para la inactivación térmica de coliformes fecales, *Salmonella* spp. y huevos de helmintos. En las pruebas por lotes de Post-AD, se determinó un periodo de 27 d para la reducción del 38% de los sólidos volátiles con una carga volumétrica aplicada (CVA) de 0.65 kg SV $m^{-3}d^{-1}$. Cuando el proceso Pre-AD fue evaluado por lotes, 13 d de tratamiento fueron suficientes para cumplir con el criterio de estabilización, con una CVA 1.25 kg SV $m^{-3}d^{-1}$. En las pruebas de operación semi-continua, el proceso Pre-AD pudo ser operado con una CVA de 3 kg SV $m^{-3}d^{-1}$, mientras que el proceso Post-AD sólo alcanzó una CVA máxima de 1.5 kg SV $m^{-3}d^{-1}$. Las bacterias y huevos de helmintos fueron inactivados a 70 ºC durante 1 h y 80 ºC a 2 h, respectivamente.

Palabras clave: digestión anaerobia - térmica de lodos, digestión térmica- anaerobia de lodos, inactivación térmica de patógenos, parámetros cinéticos.

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1 Introduction

With the high content of pathogenic microorganisms present in the sludge that is produced in Mexico, the implementation or development of technologies for the stabilisation of this sludge is focused on its sanitisation and the reduction of its organic compounds (Méndez-Contreras *et al*., 2009a; 2008). The use of biosolids in agricultural soils is practised worldwide, but the presence of pathogenic microorganisms limits its use (Arthurson *et al*., 2008 and Vigueras-Carmona *et al*., 2013). Many current technologies use chemical agents such as CaO, O_3, H_2O_2, NH_3 and CH_3COOOH (Mendez *et al*., 2009a; Park *et al*., 2008; Neyens *et al*., 2003; Pecson *et al*., 2007 and Stampi *et al*., 2001) for the inactivation of pathogenic microorganisms. However, these processes are more costly and some of them may even increase the mass of the treated sludge.

In the first part of this study (Méndez-Contreras *et al*., 2009b), it was demonstrated that the mesophilic anaerobic digestion could reduce organic matter by 38% in terms of VS, fulfilling the criterion for reducing the attraction of vectors. Nevertheless, under mesophilic conditions, the digested sludge must be pre- or post-treated to inactivate pathogenic microorganisms because only low concentrations of pathogenic bacteria (2 log units) can be inactivated at 35°C. Furthermore, the thermophilic anaerobic digestion process was capable of supporting a high organic load and inactivating faecal coliforms, *Salmonella* spp. and helminth ova, thus meeting the permissible limits for class A biosolids (US-EPA, NOM 004 SEMARNAT 2002). The disadvantage of this process is that it has to be operated consistently at a high temperature (55°C). The least expensive options to treat sludges with high pathogenic contents are being investigated in Mexico because of its socioeconomic concerns. A cheap alternative for stabilising sludge is the mesophilic anaerobic digestion process that is operated at 35°C, which is capable of significantly reducing the quantity of organic matter (specifically, volatile solids) with just one short thermal pre-treatment stage for the inactivation of the pathogens. The current study proposes the development and comparison of the sludge anaerobic-thermal and thermal-anaerobic digestion processes based on the operational conditions that were obtained from both the anaerobic and thermal process stages. Additionally, the results from a thermal inactivation kinetic model were used to describe the inactivation of faecal coliforms, *Salmonella* spp. and helminth ova during the thermal treatment stage.

2 Materials and methods

2.1 Sludge and biosolids characteristics

The raw wastewater sludge was supplied by a food industry (bird slaughterhouse) wastewater treatment plant located in Orizaba, Veracruz (Mexico). The treatment consisted of an advanced primary treatment (APT) process, which was also known as a chemically enhanced primary process. The microorganisms were characterised by quantifying the faecal coliforms, the *Salmonella* spp., and the helminth ova using the methods that were established by the Mexican Official Standard NOM-004-SEMARNAT-2002 and were based on US EPA regulations (US EPA, 1994). Laboratory testing did not observe the presence of helminth ova in the raw sludge, which was most likely because of the sanitary controls that were implemented by the poultry industry. Therefore, to evaluate the inactivation of these parasite ova, samples with known concentrations of helminth ova (100 *Ascaris* spp. ova ℓ^{-1}) were prepared. The physicochemical characterization of the sludge included determining the total solids content based on Standard Method 2540B (APHA-AWWA-WEF, 2005), the total volatile solids content (2540E SM) and the pH. The temperature was measured by using a thermocouple. The alkalinity ratio was determined in terms of partial alkalinity (pH end point 5.75) and total alkalinity (pH end point 4.3). The methane content in the biogas was measured by gas chromatography using a thermal conductivity detector.

2.2 Experimental setup

The egg-shaped anaerobic reactor was constructed out of fibreglass, as shown in Fig. 1. The hermetically sealed reactor had a capacity of 10 litres (8.5 ℓ of effective volume) and an external dry heating system that uses an electric inter-heat exchanger to control the temperature from 15°C to 110 ± 1°C. The system was equipped with alarms to indicate when the temperature exceeded a pre-set range and with a 1 liter-tank in which the thermal inactivation experiments were conducted. The inlet and outlet flow paths of this system could be modified to operate either in the Pre-AD or Post-AD modes.

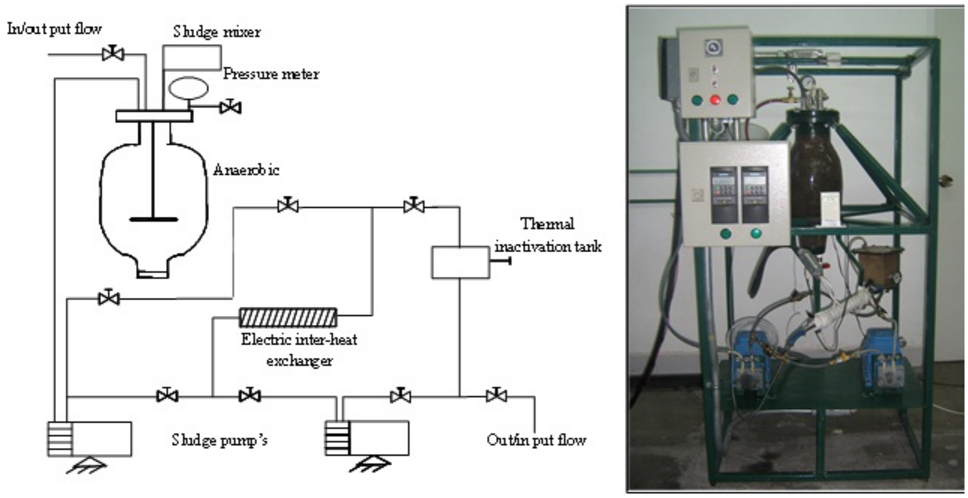

Fig. 1. Hydraulic diagram of the egg-shaped anaerobic reactor.

2.3 The thermal inactivation tests

To assess the effect of temperature on bacterial inactivation, thermal inactivation tests were conducted in a hermetically sealed 1litre tank. Samples maintained at 25°C were used as controls with an initial concentration of 2.4 $\times 10^{10}$ and 2.4 $\times 10^5$ MPN g^{-1} TS for faecal coliforms and *Salmonella* spp., respectively. The thermal treatments were conducted by applying external heat to increase the temperature from 45°C to 70°C stepwise at 5°C intervals. After one hour of exposure, the final concentrations of the microorganisms were evaluated in all the experiments. The thermal treatment was applied to the raw sludge as the Pre-AD process and to the digested sludge as the Post-AD process. To inactivate the helminth ova, the sludge samples were exposed directly to temperatures ranging from 35°C to 90°C for a 2 hour period. In each thermal treatment experiment, five samples were analyzed.

2.4 Kinetic parameters of the thermal inactivation of pathogenic microorganisms

The inactivation of bacteria described by kinetic models for disinfection reactions is similar to that described by the models that are used for chemical reactions. Currently, the predominant disinfection model is the Chick-Watson model (Méndez *et al.*, 2008), which is expressed in Equation 1:

$$\log \frac{N}{N_o} = -kC^n t \tag{1}$$

where N_o is the initial concentration of the microorganisms, N is the concentration of surviving microorganisms at time t, k is the pseudo first-order reaction rate constant, C is the disinfectant concentration and n is a dilution coefficient, which is an empirical dimensionless factor that is frequently assumed to have a value of 1. Hom proposed an alternative to the Chick-Watson kinetic model to account for deviations that are commonly encountered in practice, as shown in Equation 2:

$$\log \frac{N}{N_o} = -kC^n t^m \tag{2}$$

Where m is the Hom empirical constant and the other symbols are as described in Equation 1. Based on the results that were obtained from the thermal treatment process, the temperature dependence of microbial inactivation was evaluated using a modified first order mathematical model. The modified Hom model is shown in Equation 3:

$$\log \frac{N}{N_o} = -kT^n \tag{3}$$

Where: T is the temperature (°C), $k*$ is a constant associated with the constant of inactivation k and the time t^m, n is an empirical constant for heat diffusion.

2.5 The Pre-AD process

In this process, the raw sludge was treated thermally at 90°C for 2 hours before being processed by anaerobic digestion. The ovoid reactor was fed with a mixture containing 6400 mL of the thermally sanitized sludge with a TS composition of 2.7% and a VS composition of 1.62% (16.25 g VS ℓ^{-1}) and 1600 mℓ of an inoculating anaerobic biological sludge that was obtained from an Inverse Fluid Bed Reactor (IFBR) wastewater treatment reactor at a volumetric ratio of 80:20. The digester was operated as a batch reactor. The physicochemical characterization of the sludge was conducted daily in triplicate, and the efficiency of the process was quantified by determining the daily removal rate of the volatile solids and the amount of biogas that was produced.

2.6 *The Post-AD process*

The initial conditions at the beginning of this process were 3.6% TS and 1.83% VS (18.54 g VS ℓ^{-1}) at 35°C. At the end of the digestion period, the thermal tests were performed. The sampling frequency and the answer variables were evaluated in the same way that the parameters in the Pre-AD process were evaluated. For the Pre-AD and the Post-AD processes, the reactors were initially operated in batch mode to remove 38% of the volatile solids to stabilize the sludge. After the sludge was stabilized, each reactor was operated semicontinuously, and the organic loading rate was increased every 30 days. The initial organic loading rates were 1 kg VS m^{-3} d^{-1} for the Pre-AD process and 0.5 kg VS m^{-3} d^{-1} for the Post-AD process. The volatile solids removal was analyzed to evaluate the performance of the reactors. The microbiological contents (faecal coliforms, *Salmonella* spp. and helminth ova) were evaluated at the end of each treatment process, and the kinetic parameter values were obtained from a modified Hom kinetic model using a non-linear least squares method.

3 Results and discussion

3.1 *Characterization of raw sludge and biosolids using Pre-AD and Post-AD processes*

Concentrations of volatile solids exceeding 50% of the total solids, faecal coliform levels (10 Log MPN g^{-1} TS) and *Salmonella* spp. levels (5 Log MPN g^{-1} TS) were found in raw sludge (Table 1). The pH value was 7.26, which is characteristic of anaerobically treated sludges. The pH values are a range from neutral to slightly alkaline; pH values ranged from 6.88 to 7.87, these initial values do not affect the anaerobic treatment and they can be commonly detected in anaerobic digestion processes or in sludge from the food processing industry (Ruiz-Espinoza *et al*., 2012).

3.2 *Sludge batch digestion*

During the anaerobic digestion stages, the organic matter contained in both the raw sludge (Post-AD) and in the sludge that was thermally treated prior to digestion (Pre-AD) was reduced by 38%, as shown in Fig. 2. These results are in line with option 1 of the US EPA (1994) requirements for reducing vector attraction, which requires the removal of at least 38% of the organic matter for the treated material to be classified as a biosolid. Approximately 27 days of treatment time was required for the Post-AD process compared to the 13 days requirement for the Pre-AD process to comply with this criterion. The reduction in the treatment time is related to the partial solubilization of compounds of the sludge, which is attributed to the disruption of chemical bonds in the membranes and cell walls giving rise to the cell damage and lysis induced by thermal treatment, releasing the cellular material (polysaccharides, lipids, proteins and nucleic acids) into the aqueous phase, which is more easily available for subsequent bacterial degradation after the thermal treatment (Pre-AD process) (Ruiz- Espinoza *et al*., 2012 y Vigueras-Carmona *et al*., 2011). While the carbohydrate and lipid components of the sludge are easily degradable, the proteins are protected from enzymatic hydrolysis by the cell wall. Thermal pre-treatment at a low temperature range of 60 °C to 180 °C destroys the cell walls and makes the proteins accessible for biological degradation (Nayens & Baeyens 2003). The solubilization of the biological compounds leads to a reduction in the treatment time and an increased anaerobic digestion treatment capacity.

Table 1 summarizes the evaluated parameters of the raw sludge, Pre-AD and Post-AD processes. It can be observed that the Pre-AD process is able to reduce the treatment time by 51%, even when it is operated at an organic loading rate that is double that of the Post-AD process (1.25 kg VS m^{-3} d^{-1} compared with 0.65 kg VS $m^{-3}d^{-1}$), which considerably increases the speed and the capacity of the anaerobic digestion stage. The alkalinity ratio and the pH values were similar and acceptable for the stability of the anaerobic digestion process. Noyola and Tinajero (2005) cited a value of α= 0.48 for the continuous operation of an anaerobic sludge digestion process.

Table 1 Operating data during the different experimental stages.

Parameters	Raw sludge	Digested sludge by Pre-AD	Digested sludge by Post-AD	Units
pH	7.26 ± 0.04	7.3± 0.1	7.4 ± 0.3	
Temperature	20 ± 2	35 ± 1	35 ± 1	°C
Totals solids (TS)	2.7-3.6	1.86	2.1	% w/w
Organic matter (VS)	1.5-1.83	0.96	0.92	% w/w
Treatment time *	-	13	27	Days
Alkalinity ratio	0.37 ± 0.03	0.48 ± 0.02	0.49 ± 0.02	Alk 5.75 / Alk 4.3
Faecal coliforms	10.46	<0.47	9.46**/<0.47***	Log MPN/g TS
Salmonella spp.	5.46	<0.47	4.3**/<0.47***	Log MPN/g TS
Helminth ova	100****	-	-	HO/g TS

*Treatment time to reduce 38% VS; **Before the thermal process; *** At the end of the Post-AD process; ****Prepared solutions with 100 HO ℓ^{-1}

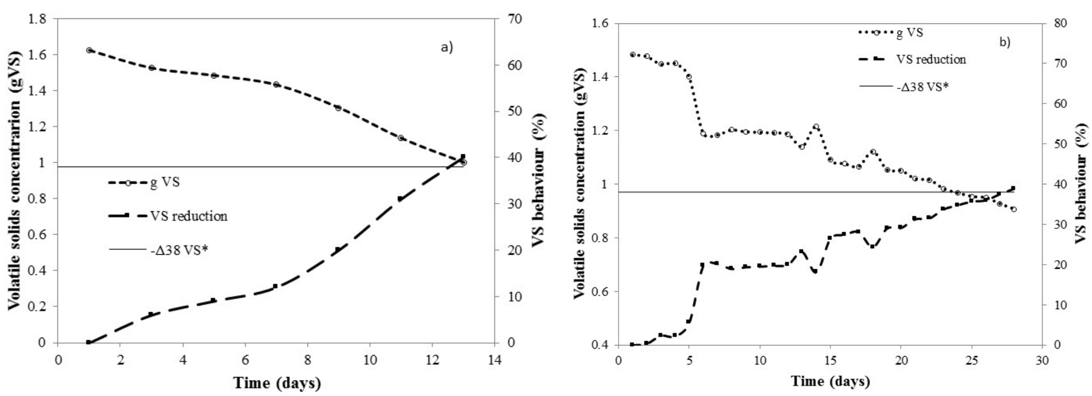

Fig. 2. Behavior of the removal of volatile solids during the sludge digestion in Pre-AD (a) and Post-AD (b).

The production of biogas ranged from 900 mℓ d^{-1} to 4550 mℓ d^{-1} for the Pre-AD process and 1000 mℓ d^{-1} to 2100 mℓ d^{-1} for the Post-AD process and the maximum biogas production was achieved between Days 6-8 and Days 21-28 of the operational period.

3.3 Kinetic parameters of the thermal inactivation of pathogenic microorganisms

During the Post-AD process operation, it was demonstrated that the initial digestion of the sludge removed 1 and 1.1 log units of the faecal coliforms and the *Salmonella* spp., respectively (Table 1). These results are very similar to those reported by Riua *et al*., (2010) for the mesophilic anaerobic digestion (MAD) of a combination of primary and activated sludge at a HRT of 21 d, and our results are slightly lower than 1.7 log units for *E. coli* and 2.1 log units for *Salmonella Senftenberg* that were obtained by Horan *et al*., (2004) for the MAD of wastewater sludge with an HRT of 12 days. As a result of the thermal inactivation of microorganisms, the reduction in faecal coliforms ranged from 0 to 8.5 log units, and the biosolids that were produced met the Class A limits. Exposing microorganisms to temperatures between 40 °C and 50 °C for 1 h inactivated between 2.7 log units and 3.2 log units of faecal coliforms (Fig. 3a); however, the results indicate that the temperature should be increased to 55°C to ensure that the final concentrations meet the class B limit for biosolids. Higher temperatures reduced the densities of the faecal coliforms to an average of less than 1 log unit, and the response

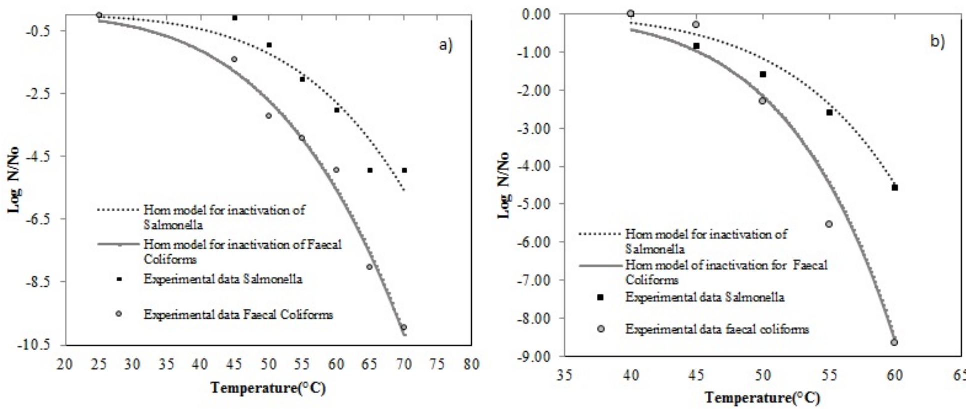

Fig. 3. Inactivation of *Salmonella* spp. and faecal coliforms concentrations in Pre-AD (a) and Post-AD (b) with thermal treatment for 60 min.

of *Salmonella* spp. to different temperatures was similar to that of faecal coliforms. The initial bacterial concentrations were approximately 4 log units, but these concentrations were reduced by approximately 2 log units after exposure to a temperature of 50°C for 1 h. By exposing these microorganisms to temperatures of 60°C or higher, the final concentrations were reduced to levels below the detection limits (Fig. 3b). Lang *et al*., (2008) report the instantaneous death of enteric bacterial cells in sewage sludge at a temperature of 70°C.

In the case of helminth ova, the most favorable temperature for inactivation to meet the classification conditions for class A biosolids was between 80°C and 90°C for both processes. No significant differences that could be attributed to the direct interference of the organic matter with the inactivation were found. *Ascaris* spp necessitated exposure to a temperature of 80°C for 120 min to meet the Mexican regulation of 1 HO g^{-1} TS for class A biosolids (Fig. 4). Similar conditions were presented by Maya *et al*., (2010), who reported a complete inactivation of helminth ova at a temperature range of 70-80°C after 120 minutes of exposure when they used sludge samples with a TS content of 20%.

The calculated kinetic parameters for the thermal inactivation are show in Table 2. Mendez *et al*., (2004) mentioned that for the chemical inactivation of pathogens using ammonia in physicochemical sludge, $k*$ values are significantly higher than 1 suggesting that microorganism are not very resistant to the inactivation. In this case, $k*$ values are lower than 0 suggesting that under these experimental conditions, the microorganisms are highly resistant to temperature in a range of 25 up to 50°C; however, there was a significant inactivation of bacteria from 55°C to 70°C.

The values observed for the heat transfer coefficient "*n*" may be a result of the heat diffusion that was produced under experimental conditions for the pre and post thermal treatments. The values of the parameter "*n*" for the Post-AD process are higher in comparison with Pre-AD process; this effect may be explained because that the morphology of aggregates is more complex in a raw physicochemical sludge (used in Pre-AD) and the pathogenic microorganisms found in wastewater are trapped in the sludge floc matrix formed from the coagulation process, this phenomenon interferes in the heat diffusion when the thermal pre-treatment is applied. Due to biochemical transformations in the anaerobic digestion process, the morphology of aggregates is simplified and a better heat diffusion was observed when the post-thermal treatment was applied.

Furthermore, the kinetic coefficients obtained after 60 minutes from the experimental data can be substituted into Equation (3) to predict the inactivation of the studied group of microorganisms that are present in the sludge when heat is used in the Pre-AD and the Post-AD processes to increase their operational efficiencies (Figures 3 and 4).

The inactivation of bacteria and helminth ova in the Pre-AD and the Post-AD processes shows a typical behavior known as "shoulder effect" (Albert and Mafart, 2005), which confirms that the evaluated groups of microorganisms are resistant to inactivation at relatively low temperatures (Figs. 3-4). These results can be used to design and operate a mesophilic anaerobic system improved with pre or post thermal treatment of wastewater sludge.

Table 2 Summary of the kinetic parameters for the modified Hom model.

Microorganisms	Time (min)	Pre-AD			Post-AD		
		k^*	n^*	R^2	k^*	n^*	R^2
Faecal coliforms	60	5.86x10^{-7}	3.923	0.98	3.032x10^{-13}	7.57	0.96
Salmonella spp.	60	2.58 x10^{-8}	4.516	0.91	3.40x 10^{-13}	7.37	0.97
Ascaris spp.	120	1.311x10^{-2}	1.276	0.79	2.126x10^{-3}	1.6	0.89

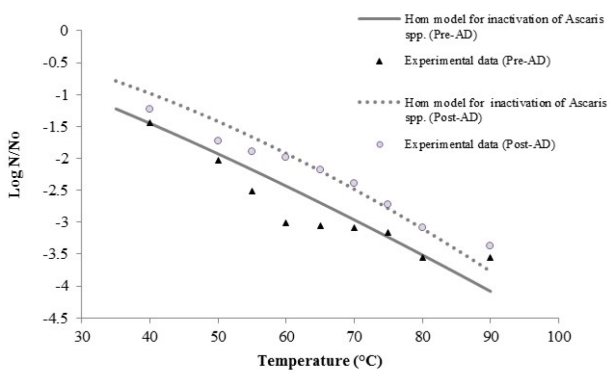

Fig. 4. Inactivation of *Ascaris spp* concentrations in Pre-AD and Post-AD with thermal treatment for 120 min.

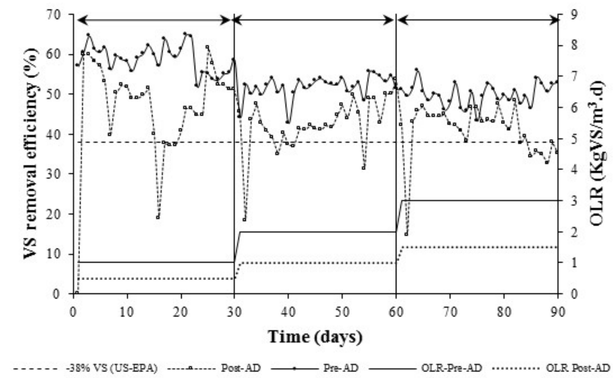

Fig. 5. VS removal efficiency in Pre-AD and Post-AD.

Table 3 Comparative performance parameters in Pre-AD and Post-AD.

Continuous Operation period (d)	HRT (d)		OLR kg VS m^{-3}d^{-1}		Average biogas production (ℓ d^{-1})		Average VS removal (%)		Average Methane yield ℓ g^{-1} VS rem	
Anaerobic digestion										
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
(1) 1-30	22.0	40	1	0.5	2.14±0.25	1.37±0.36	58.81±3.42	46.68±12.5	0.82±0.12	0.5±0.1
(2) 31-60	11.0	20	2	1	3.6±0.27	2.13±0.26	51.78±2.82	42.47±6.7	0.81±0.08	0.52±0.14
(3) 61-90	7.6	15	3	1.5	5.2±0.32	2.48±0.46	49.9±2.73	40.85±6.49	0.81±0.07	0.5±0.16

3.4 Semicontinuous anaerobic sludge digestion

The volatile solids removal efficiency, together with the OLR that was applied in the Post-AD and Pre-AD processes, is shown in Fig. 5. The first reactor was for the Pre-AD process, and the second reactor was for the Post-AD process. A low initial OLR of 1 kg VS m^{-3} d^{-1} was used for the Pre-AD process, and the OLR was 0.5 kg VS m^{-3} d^{-1} for the Post-AD process. During the first operation period (from 1-30 d), the average VS removal rates were 58.81% and 46.68% for the Pre-AD and the Post-AD processes, respectively (Table 3). A large HRT was applied at 22 d for the Pre-AD process and at 40 d for the Post-AD process. The methane yield was approximately 0.5 ℓ g^{-1} VSdestroyed for the Post-AD process and 0.82 ℓ g^{-1} $VS_{destroyed}$ for the Pre-AD process, which was similar to the yields obtained by Jolis (2008), who showed a methane yield between 0.8 and 1.1 ℓ CH_4 g^{-1} $VS_{destroyed}$ for municipal sludge that underwent a thermal hydrolysis pre-treatment stage at 170°C for 25 minutes. An increase in the OLR to 2 kg VS m^{-3} d^{-1} for the Pre-AD process and 1 kg VS m^{-3} d^{-1} for the Post-AD process in second period (31-60 d) was evaluated. A slight decrement in the VS removal was obtained for both processes because of the new OLR. In the third period, the Pre-AD process was fed with an OLR of 3 kg VS m^{-3} d^{-1} and the Post-AD process was fed with an OLR of 1.5 kg VS m^{-3} d^{-1}. During this operational period (60 - 90 d), both processes experienced a decrease in VS removal of approximately 9% for the Pre-AD process and 5% for the Post-AD process. VS removal averages of 49% for the Pre-AD process and 40.8% for the Post-AD process were obtained. Although the average

VS removal in the Post-AD process exceeded the 38% removal that is required for compliance with the biosolids regulations, the average removal in the last 7 days of operation did not exceed 38%, which was indicative of a shock load in the reactor. The HRT was reduced in conjunction with an increased OLR in both processes, where the HRT in the Pre-AD process was 7.6 d and the HRT in the Post-AD process was 15 d. The methane production was stable in both processes during the three operational periods, and the amount of methane produced by the Pre-AD process was 62% more than the amount of methane produced by the Post-AD process.

Conclusions

The obtained results demonstrate that the Pre-AD process presents significant advantages in comparison with Post-AD process. The application of heat to reach temperatures up to 90°C during 2 hours can significantly reduce the anaerobic treatment time; increase the methane yield, and inactivate the high concentration of bacteria and helminth ova present in the raw sludge, also increasing the capacity of the treatment process to support higher organic loads (3 kg VS/m^{-3}d^{-1}).

The Post-AD process produces biosolids that are free of biological contamination and can be used directly on the roots of plants without restriction, however, not accelerating the digestion process.

The kinetic parameters estimated in this investigation can be used to determine the design and operation methods of the Pre-AD or Post-AD processes and can be used as a starting point for identifying the optimal operating temperatures of the thermal process.

The Pre-AD and Post-AD processes can be considered as effective alternatives to quicklime stabilization, ammonia sludge stabilization, and thermophilic anaerobic digestion. The selection of the appropriate process to treat sludge with extremely high pathogenic content should be based on aspects such as the production costs and the viability of their applications and an advantage of the proposed processes in this study is that only one device allows the dual operation for both the Pre-AD or Post-AD modality.

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