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Temperature-phased anaerobic digestion of Industrial Organic Fraction of Municipal Solid Waste: A batch study

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HIGHLIGHTS

- Temperature-phased anaerobic digestion has been studied.
- Industrial OFMSW from non-selective collection systems has been digested.
- Thermophilic–mesophilic temperatures, dry condition and batch, have been selected.
- Different thermophilic times were analyzed.
- The methane yield and the organic material removal in each time were studied.

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ABSTRACT

Anaerobic digestion of the Organic Fraction of Municipal Solid Wastes from non-selective collection systems is widely implemented at industrial scale. Classically, single-temperature anaerobic digestion systems (mesophilic or thermophilic) have been used although some limitations were found in the processes performance. However, the specific advantages of the two processes could be exploited by using a temperature-phased anaerobic digestion (TPAD). Thus, in this paper, the application of a TPAD process without microbiological separation (thermophilic 55 °C–mesophilic 35 °C) to the biomethanation of OFMSW has been studied.

The TPAD assays were carried out in batch reactors. The processing times for the thermophilic (55 °C) stage have been located in the range from 12 to 3 days. After the first stage, the waste treatment was continued in a second mesophilic reactor (35 °C) until completing the degradation process.

The higher values for the organic matter removal (VS removal 82–85%) and the maximum specific growth rates of microorganisms (0.31–0.43 days-1), were obtained for thermophilic phase operation at 5 and 4 days, respectively. Lower operation times, namely 3-days, for thermophilic first-phase are viable and the methane productivity obtained was comparable with respect to that obtained in the above mentioned conditions (0.6 L/gVS$_{removed}$). However, in this conditions, a decrease in the maximum specific growth rate of microorganisms (0.26 days^{-1}), a lower SV removal (75%), and a higher final amount of non-biodegradable substrate (1231 mg/L) were obtained, working at 3 days, despite of using higher operational times (29 days). According to these results, it can be concluded than the optimum time for the thermophilic first-phase in TPAD would be between 5-days and 4-days.

1. Introduction

The growth of societies and the rapid urbanization in determinate places implies an increment in the generation of Municipal Solid Wastes (MSW). A high proportion of generated MSW is organic matter, also known as the Organic Fraction of Municipal Solid Waste (OFMSW). This fraction can be valorised energetically. Thus, various alternatives have been proposed to minimize the negative impact of this type of waste. One of the most widespread technologies for the treatment of the organic wastes is the biomethanisation or anaerobic digestion (AD).

AD of organic material can be an ecological alternative to the traditional management of the organic solid wastes (landfill) because reducing methane emissions and by providing energy:

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biogas contains about 60–70% of methane. Additionally, an effluent with a low organic content is obtained from the AD which can be used in an agronomic valorisation, that is, as compost. Usually, the process is carried out in a single stage of temperature. Temperature is one of the main process variables because it determines the economic balances and the process performance (the methane yields and the organic matter removal efficiency).

The anaerobic microorganisms are classified according to the optimum temperature range in which they grow up: psychrophilic ($T < 20$ °C), mesophilic (20 °C < T < 45 °C), thermophilic (45 °C < T < 60 °C) and hyperthermophilic ($T > 60$ °C). The most common temperatures in anaerobic digestion of organic wastes are thermophilic and mesophilic. The thermophilic systems are more effective due to the higher metabolic rates of microorganisms [1] and besides, a higher destruction of pathogens. The operation at mesophilic temperatures (33–37 °C) is more stable and requires less energy expenditure. Moreover, the advantages of the mesophilic process indicate that there are less probability of inhibition by ammonium [2] and long chain fatty acids [3].

TPAD combines two temperature ranges, normally thermophilic and mesophilic, in one global process, maximizing the advantages and avoiding the disadvantages of the single-temperature operation. In general, the hydrolytic–acidogenic reactor operates at thermophilic temperature and the methanogenic reactor at mesophilic temperature. Normally, there is a separation of the microbiological phases according to the temperature.

This process was established in the 1990s [4–5] studying systems with low solid content as whey or activated sludge. This type of system in temperature phased manages to improve the hydrolysis of the organic waste [6], which is the limiting step of the process, increasing the process stability and a higher efficiency in the production of biogas regards to the amount of organic matter fed to the system [7]. Currently studies are develop in order to achieve these advantages with different wastes and different combinations of temperature ranges: hyperthermophilic (70 °C)–thermophilic (55 °C) [8–9] or thermophilic (55 °C)–mesophilic (35 °C), which is the most common technology and the configuration used in this study. Thus, some authors recommend starting the process with a thermophilic phase because is more effective [10] than the mesophilic temperature. The combination of both processes may lead to a more efficient process that allows combining the advantages of the two temperature ranges: the first, thermophilic range, in order to promote hydrolysis of the waste and then, the mesophilic one to ensure higher process stability.

Usually, the TPAD has been used with sewage sludge and organic wastewaters. The thermophilic first-phase accelerates the limiting step of anaerobic digestion of particulate organic matter and achieves sterilization of pathogenic waste [11–13], allowing the subsequent agronomic use of effluent. The TPAD can also improve the dewaterability of the sludge [14–15]. Demirer and Othman [16], have studied the temperature-phased anaerobic digestion of activated sludge in batch reactors. The acidogenic reactor was operated in thermophilic range of temperature and its effluent was treated in the subsequent methanogenic mesophilic reactor. The operating time in the thermophilic reactor was between 2 and 4 days and the anaerobic process was completed in the mesophilic reactor. The main results show that TPAD reached a higher CODs removal (26–49% higher) than single-stage process for the same operation time. In this regard, Schmit and Ellis [17] compared the efficiency of thermophilic single-phase with TPAD in the codigestion of sewage sludge and OFMSW. These authors found more efficient volatile solids destruction and higher methane rate in TPAD.

In addition, there have been studies of co-digestion with other waste in temperature-phased systems. It should be noted the study of Kim et al. [18] who used food waste in co-digestion with sludge in TPAD. Lee et al. [19] have developed a mathematical model for a temperature-staged system applied to the treatment of dog food mixed with maize flour. The model provides a good fit of the experimental data.

This paper describes the results of an experimental study conducted to study batch TPAD applied to the treatment of OFMSW from non-selective collection systems. The TPAD system is carried out without microbiological separation, that is, the inoculum includes the entire microbiological consortium and the natural selection is acting according to the external conditions. The TPAD includes a first step performed at thermophilic range (55 °C) and a second stage operated at mesophilic temperature (35 °C). The selected configuration aims to accelerate the limiting step for the anaerobic process of the OFMSW – namely the hydrolysis – during the thermophilic first-stage. Besides, the objective of the mesophilic second-stage is to increase the stability of the process, diminishing the risk of inhibition by ammonia and reducing the concentration of volatile fatty acids. Thus, based on the previous evidences, it is expected that the concatenation of the two stages allows a faster process and, simultaneously, reaches a higher degree of degradation of organic matter contained in the OFMSW, maximizing the amount of biogas produced.

In short, the objective of this paper has been to characterize and optimize the operating conditions of the TPAD (Temperature Phased Anaerobic Digestion) for industrial OFMSW in batch conditions. It should be pointed out than the novelty of the study lies in there are a very few papers in literature about the application of the temperature-phased reactors to the treatment of OFMSW by anaerobic digestion process with a high solid content (dry anaerobic digestion). Furthermore, the novelty of the present study temperature-phased is that it has been not accomplished with the separation of microbiological communities and, hence, the two reactors in TPAD contain all the microorganisms groups constituting the overall anaerobic microbiota.

2. Materials and methods

2.1. Experimental design

The study was carried out in Continuous Stirred Tank Reactors (CSTR). The reactors were operated in two phases: First phase in thermophilic (55 °C) and in a second phase in mesophilic (35 °C). All the organic load of the reactor was added in the thermophilic phase. Several times were tested in thermophilic and once time that time in thermophilic was all over, the reactors were filled with mesophilic inoculum and incubated at 35 °C until completed biodegradation. In the Fig. 1 an experimental scheme of the study can be observed.

Two runs of experiments were conducted in order to analyze the effect of the operation time of the thermophilic first-phase on the TPAD applied to OFMSW. In first series (preliminary tests) a wide range operation times have been tested for the thermophilic reactor. Later, in the second series of experiments (specific tests), the study has been focussed on the more suitable range as suggested by previous results:

- Preliminary single-stage thermophilic test. A previous test was performed to study the organic matter solubilisation in function of time in a thermophilic batch assay.
- Preliminary TPAD tests. The following operating times for the thermophilic-phase have been tested: 12, 6 and 3 days (called 12T, 6T and 3T, respectively). The main objective was narrowing the optimum range of operating times to design the later experiments.
- Specific TPAD tests. On the basis of information obtained in the preliminary test, the following operating times were tested: 6, 5, 4 and 3 days (called 6T, 5T, 4T and 3T, respectively). The objective in this case was to determinate the optimum operating time for the thermophilic first-phase reactor in the TPAD.