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Co-digestion and model simulations of source separated municipal organic waste with cattle manure under batch and continuously stirred tank reactors

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ABSTRACT

This study investigates the co-digestion of source separated municipal organic waste (SSMOW), pretreated using a biopulper, and cattle manure both in batch and continuous stirred tank reactors. The optimum co-digestion feeding mixture was consisted of 90% SSMOW and 10% cattle manure on organic matter basis, yielding 443 $mLCH_4/gVS$. The high performance of the co-digestion was explained by the fact that the efficient pulping pretreatment boosted the methane production from SSMOW and that the added livestock slurry provided the buffer capacity to avoid inhibition occurred by intermediates' accumulation. Moreover, batch assays focused on the effect of inoculum to substrate ratio (ISR) were performed. Results showed that the reduction of ISR had slight impact on extending the lag phase, without affecting the rest kinetic parameters. The efficiency of the co-digestion process in continuously fed reactor was comparable with the results obtained from the batch assay (i.e. $<$ 95% of the maximum expected value). Finally, the outputs from an applied mathematical model were in good agreement with the experimental data obtained from the continuous reactor operation, demonstrating that the BioModel can serve as a reliable tool to predict the process performance under real-scale conditions.

1. Introduction

Anaerobic digestion (AD) of source separated municipal organic waste (SSMOW) is considered as a competitive to the traditional (e.g. composting, landfilling, incineration) waste management solution as the organic matter is efficiently degraded producing bioenergy and also, biofertilizer [1,2]. In terms of bioenergy production, SSMOW can ensure high biogas yielding operation [3–5]. Specifically, the presence of soluble carbohydrates, proteins and lipids derived from the kitchen waste residues [6] settles SSMOW as a very interesting substrate for AD.

Despite the fact that SSMOW consists mainly of degradable components, non-degradable fractions (e.g. plastics) can be also found, as impurities. Thus, a well-performing separation step can increase process efficiency by initially discarding the non-degradable materials and subsequently, a suitable pretreatment method can boost the deconstruction of previously intact organic matter [7–9]. In industrial perspective, it was previously shown that the integration of two rather dissociated processes into a single and straightforward step is able to remarkably enhance the AD sustainability [10].

In this framework, pulping technology similar to the process used in paper industry can combine these two steps namely separation and pretreatment steps that are needed prior to AD of SSMOW, into a single process. A biopulper can separate the degradable organic matter and sort-out the non-degradable that can be subsequently recycled, reused or recovered [11]. In addition, the installed milling machinery assists the pretreatment of organic matter improving the biodegradability of SSMOW. In fact, a previous study demonstrated that the pretreatment of SSMOW with pulping technology, led to more than 390 $mLCH_4/gVS$ under different reactor configurations (i.e. batch assays, fed-batch and continuous stirred tank reactors (CSTR)) [5].

Notwithstanding the high bioenergy output, SSMOW is a very acidic waste, and on top of this, the AD process is prone to be inhibited at increased organic loads [1]. Thus, it is crucial to ensure high bioenergy output avoiding risks of acidification incidents and indeed, co-digestion can serve as a potential solution to such inhibition problems. More specifically, cattle slurry is able to increase the pH towards higher levels and hinder reactor's acidification due rapid volatile fatty acids (VFA) accumulation [12]. In addition, various hydrolytic and fermentative microbes which accelerate the disintegration process are already present in the livestock manure. So, the dissimilar biochemical characteristics of SSMOW and manure substrates can be combined to create a proper feedstock mixture. Furthermore, the usage of livestock slurries into the biogas sector is promoted by the policy-makers by the granted subsidies as mean to solve the manure treatment problem through AD [13]. Thus, co-digestion strategies using livestock manures are highly exploited.

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However, the chemical composition of both substrates is not consistent but is strongly dependent on different parameters, which will in turn affect the final methane productivity. For instance, the major origin of SSMOW can influence positively (e.g. food residues) or negatively (e.g. green waste) the final bioenergy output [14]. On the other hand, nutritional feedstock composition, moisture content, animal species and growth stage are among the parameters that markedly affect manure's biogas productivity [15]. Hence, a universal feeding recipe for the biogas plants is not possible and thus, the optimum feedstock composition should always be independently examined within the framework of co-digestion applications.

Apart from the optimum co-digestion mixture, other kinetic parameters of the AD process are equally important and should be evaluated. For example, the achievement of a rapid and efficient disintegration of organic matter is assigned to the ratio between added feedstock and active biomass [16]. Indeed, organic overload inhibits the methanogenic community due to VFA accumulation and over-acidification [17]. Thus, kinetic parameters such as lag phase, hydrolysis and methane rate are influenced by the inoculum to substrate ratio (ISR) [18]. The imbalance between rapid hydrolysis-acidification and slow methanogenesis causes organic overload to the archaeal species which could not fully utilise the fed substrate [19]. Hence, it is crucial to secure an efficient feeding strategy to avoid toxicity that can eliminate the methanogenic activity.

Furthermore, operational parameters (e.g. reactor's configuration) play an important role towards co-digestion process optimisation. For instance, batch reactors can efficiently provide information about the duration of lag phase, maximum biogas yield, methane and hydrolysis rate. In contrast, CSTR are more appropriate to examine issues as microbiome's acclimatization at long term operation. Experiments are laborious and time consuming and therefore can only cover few experimental conditions. On the contrary, the outcome of both lab-scale reactor set-ups after data interpretation can be extremely useful as input for modeling simulations in order to expand testing at various conditions, and thereby improve the understanding of the AD system. Specifically, reliable mathematical models can reveal in advance the bottlenecks that limit the methane production (e.g. lag phase, substrates inhibition etc.) and highlight the operational conditions (e.g. hydraulic retention time, organic loading rate) that optimise process efficiency [20]. Hence, through reliable simulation outputs, the application of SSMOW for AD can be generalised in the direction of stable and high-yielding biogas production.

The aim of the present work was to provide a comprehensive research on exploitation of SSMOW as a major influent substrate for biogas digesters and to generate a dataset based on continuous reactor operation monitoring that would be used as input for mathematical modeling. Thus, mono- and co-digestion batch assays using SSMOW, pretreated using a biopulper, and cattle manure as the co-substrate were initially conducted. A subsequent batch set was performed to evaluate the kinetics of the most promising feeding mixture and to identify potential problems related to process inhibition at different ISR. Moreover, a continuously fed digester was set up to monitor and evaluate further the effect of the co-digestion process. Finally, a mathematic model (BioModel) was used to simulate the co-digestion process and validate the accuracy of the experimental work.

2. Materials and methods

2.1. Inoculum

Thermophilic inoculum was provided by a well performing lab-scale reactor fed with cattle manure. The digestate was sieved to remove the remaining organic matter and stored in thermophilic incubator for 10 days to reduce the background biogas production. The major physicochemical characteristics of the inoculum, after the degassing process, were pH: 8.36, Total Solids (TS): 26.70 ± 0.20 g/L, Volatile Solids (VS): 17.54 ± 0.22 g/L, Chemical Oxygen Demand (COD): 24.78 ± 1.19 g/L, Total Kjeldahl Nitrogen (TKN): 2.32 ± 0.09 g-TKN/L, Ammonium Nitrogen: 2.06 ± 0.10 g- NH_4^+/L and total Volatile Fatty Acids (TVFA): 0.25 ± 0.05 g/L.

Table 1
Characteristics of SSMOW and cattle manure.

Characteristics	SSMOW	Cattle manure
pH	4.05	7.24
TS, g/L	40.65 ± 0.64	48.25 ± 0.23
VS, g/L	35.00 ± 0.67	35.00 ± 0.04
COD, g/L	62.34 ± 1.78	56.99 ± 1.63
TKN, g/L	1.23 ± 0.04	2.46 ± 0.08
NH_4^+, g/L	0.29 ± 0.04	1.61 ± 0.08
C/N	19.01 ± 0.95	8.69 ± 0.43
TVFA, g/L	1.73 ± 0.05	6.73 ± 0.30
Acetate, g/L	1.54 ± 0.05	4.49 ± 0.29
Propionate, g/L	0.06 ± 0.00	1.19 ± 0.08
Iso-butyrate	0.01 ± 0.00	0.16 ± 0.00
Butyrate	0.11 ± 0.01	0.59 ± 0.02
Iso-valerate	0.01 ± 0.00	0.27 ± 0.08
Valerate	0.01 ± 0.00	0.05 ± 0.00

2.2. Substrates

SSMOW of approximately 25% (v/v) industrial and 75% (v/v) household waste were collected from Gemidan Ecogi A/S after pulping process, as previously described [11]. In brief, municipal waste is inserted into a pulper equipped with a helical rotor. The rotor agitates to disperse the bio-degradable organic matter without damaging the non-degradable fraction. Subsequently, the two fractions are separated using a perforated plate. Cattle manure was collected from Hashøj biogas plant. The substrates were diluted with tap water to reach the same content of organic matter to prevent pumping, mixing and clogging problems in the lab scale reactors. After dilution and mixing, the substrates were stored in plastic bottles at -20 °C until usage. The main chemical characteristics of the prepared substrates are presented in Table 1.

2.3. AD experiments

Biochemical Methane Potential (BMP) assays were initially performed based on Angelidaki et al. [21] in order to define the bioenergy production of the used substrates under mono- and co-digestion trials (i.e. 80:20, 60:40, 40:60 and 20:80 on VS basis). Triplicate glass reactors were used, with total and working volume of 547 and 200 mL, respectively. The inoculum represented 80% of the working volume and the organic load was 2 gVS/L. Prior to incubation, the batch reactors were flushed with pure N_2 to replace the remaining oxygen and achieve anaerobic conditions. Subsequently, they were placed in a thermophilic incubator (54 ± 1 °C). Based on the results from the first BMP test, the optimum mixing ratio of substrates in the feedstock was determined. Then, a second BMP test was set up to examine the effect of ISR on the AD of the used substrates. Specifically, batch co-digestion experiments were established at three different ISR on VS basis (i.e. 0.5, 1.5 and 3.0) keeping the amount of inoculum constant in all batches [22]. Samples for VFA determination and methane content were taken during the incubation period. For both BMP tests, daily manual stirring was conducted to avoid the creation of dead zones and monitoring of methane production was performed twice a week until cease of methane production was observed ($p < .05$).

Moreover, a continuously stirred tank reactor (CSTR) with 9.0 L total and 7.5 L working volume was used to examine the AD of the mixed feedstock under continuous mode operation. The reactor was initially filled with the same inoculum as the batch assays and flushed with pure N_2 to ensure anaerobic conditions. Based on the results from