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Can two-stage instead of one-stage anaerobic digestion really increase energy recovery from biomass?

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HIGHLIGHTS

- Two-stage anaerobic digestion should be more productive than traditional process.
- Energy recoveries ($H_2 + CH_4$ *vs* CH_4) were compared through a new method.
- Four different substrates at nine different experimental conditions were tested.
- Two-stage recovered 8%–43% more energy than one-stage and never significantly less.
- Deeper research should be addressed to prove the convenience of two-stage approach.

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ABSTRACT

The supremacy of two-stage on traditional one-stage anaerobic digestion (AD), in terms of overall energy recovery (ER) from biomass has often been proved. However, the process conditions ensuring this result, as well as the reasons for higher efficiency, have always been unclear. In this work, a new standardized approach is proposed: optimization at lab-scale of both hydrogen and methane generation processes allowed comparing the maximum potential ER of both two-stage (as $H_2 + CH_4$) and one-stage AD (as CH_4). Relatively high bio-hydrogen yields were obtained testing four different organic substrates (ER of 1–1.6 MJ $kg^{-1}_{VS\text{-}added}$). Biomethane generation resulted in ER in the range of 9–19 MJ $kg^{-1}_{VS\text{-}added}$, similarly for two-stage and one-stage systems. The overall ER resulted in significantly higher (8%–43%) for the two-stage in the large majority of experimental conditions and never significantly lower. These preliminary results should drive further research to better understand the conditions that can drive the two-stage AD to higher performance.

1. Introduction

The two-stage anaerobic digestion (AD) process has often been reported as a viable way to produce bio-hydrogen and bio-methane from a wide range of organic materials [1,2]. In the last decade, several studies were published on this topic and many authors reported different applications of the two-stage AD, with different organic substrates and different process designs [3–5].

Generally, the phase separation of hydrolysis/fermentation from methanogenesis in different reaction environments has been proposed as a strategy to increase overall process performances, in terms of stability, degradation efficiencies in both fermentation and methanogenesis phases and thereby in terms of overall energy recovery (ER) from biomass [6]. A controlled acidogenic fermentation, that allow efficient bio-hydrogen production, has been considered the best pathway to pretreat raw biomass and enhance methanogenic process.

According to various authors, efficient bio-hydrogen production and volatile fatty acids (VFA) liberation in the liquid during acidogenic phase would at the same time ensure energy recovery as H_2 and favor CH_4 production from VFA in the methanogenic reactor [7]. This with relatively negligible variation of plant structure and cost, as soon as the first stage is normally a small additional digester (10 times shorter retention time compared to the second stage) [7].

On the other hand, literature has seldom given general and exhaustive explanations to this thesis, often limiting efforts on particular case studies, with particular substrate types and operational conditions.

In particular, few studies took into account the overall potential ER of two-stage AD, compared to single-stage AD, focusing on the

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reasons and the conditions for actual enhancement of ER by phase separation. The most important contributions to this topic came from Liu et al. [8], Pakarinen et al. [9] and Luo et al. [6], that demonstrated the supremacy (from 20% to 60% higher ER) of two-stage AD at both thermophilic and mesophilic conditions. The reasons for success of two-stage system were associated, generally, to process advantages, as higher efficiency in converting VFAs into methane in the second stage [8]. Pakarinen et al. [9] obtained high advantage from two-stage AD and found significantly higher hydrolysis efficiency after the hydrogen production step, with increased soluble organic matter and VFA production through fermentation, allowing higher productivity in the methanogenic phase. Luo et al. [6] were more precise and associated the higher ER of the two-stage to higher performances in the second-stage (methanogenesis) in degradation kinetics and to the effect of minimizing the loss of relatively "fresh feed" out of the reactor due to "short-circuiting", occurring in single-stage fully mixed reactors.

More recently, Schievano et al. [10] observed two-stage *vs* single-stage AD in thermophilic continuously stirred tank reactors (CSTR) fed with a mix of fruit/vegetable waste and swine manure, focusing on the overall ER and on biological process efficiencies. In this case, equal ER resulted from the two AD systems, even if the methanogenic reactor in the two-stage system showed residual un-degraded organic compounds (VFA were 10 times higher than in the single-stage reactor) and thereby an unexpressed potential [10]. This means that, in this case, if the methanogenesis in the two-stage was not slightly inhibited, the two-stage would have shown higher ER, as compared to the single-stage. This might be obtained simply by a slight increase of the retention times and/or by improving the methanogenic activity in the second stage.

In this work, a new approach in investigating this topic is proposed. Both bio-hydrogen and bio-methane productions should be always optimized to compare the two AD systems. For this reason, optimization of bio-hydrogen production process was carried out for four different organic mixtures and the biochemical methane potential (BMP) standard tests were used to obtain optimized ER from methanogenesis.

2. Materials and methods

To verify the energy recovery, two-stage and single-stage AD were simulated in lab-scale fermenters. The test was run on four different organic mixtures of biomass, diluted with liquid swine manure (SM) to the desired organic matter concentration, measured as volatile solids (VS) per g of wet weight (ww). Indeed, SM is a very common liquid material used in biogas plants and provides both nutrients and buffer capacity to AD environments. In previous studies dealing with optimization of anaerobic dark fermentation, SM was already used as co-substrate to efficiently produce bio-hydrogen [11]. The feeding substrates were 4 organic materials, usually available in full-scale agricultural AD facilities: (a) maize silage (MS), (b) waste rice flour (RF), (c) olive pomace (OP) and (d) waste fruit/vegetable (FV).

The first-stage was run (as reported by Tenca et al. [11]) in semi-continuous reactors, fed twice a day; the optimized H_2 production were selected by varying the feeding conditions in two variables: (i) organic matter concentration (OMC) and (ii) hydraulic retention time (HRT). The pre-digested materials, produced in optimized conditions, underwent the methanogenic phase (2nd stage), i.e. incubated in batch reactors optimized for methanogenesis. The single-stage AD was run in parallel in batch reactors fed with the untreated organic mixtures. The energy recovered from the double-stage ($H_2 + CH_4$) and the single-stage (CH_4) AD systems were compared to look for possible increase in productivity in the double-stage concept. All tests were run in triplicate.

2.1. Hydrogenic process optimization (1st stage)

The hydrogenic phase of two-stage AD system was run in semi-continuously operated reactors of 500 mL capacity, fed 2-times a day, in thermophilic conditions (55 ± 1 °C), as reported in detail in a recent work by Tenca et al. [11]. A Box–Wilson central composite design (CCD) [12] was applied to study the effect of two operating parameters (the controllable factors: OMC and HRT) on biohydrogen production (the experimental response), and therefore to find the optimal region in which to operate the fermentation.

In a CCD, the experimental values of each controllable factor are defined to be uniformly distributed around a centerpoint, according to factorial design levels coded from −1 to +1. These levels are then augmented with star points that, in a two-factor CCD, are axially placed at a coded distance of $-\sqrt{2}$ and $+\sqrt{2}$ from the center of the design. As a result, OMC and HRT were investigated at five levels, coded as ($-\sqrt{2}, -1, 0, +1, +\sqrt{2}$). The level code reflects the step change in the actual value chosen for the two operating parameters.

All the evaluated levels were arranged in nine different treatments, hereafter called experimental conditions (EC), corresponding to nine combinations of OMC with HRT values. Each treatment consisted of three replicated assays. All biogas production and ER data and all chemical characterization data were reported as mean and standard deviation of the three replicates.

For all substrates, except for FV, the selected ranges for factors were 25–65 $g_{VS}\ kg^{-1}_{ww}$ and 1–4 d for OMC and HRT, respectively, with a design centerpoint of (45 $g_{VS}\ kg^{-1}_{ww}$; 2.5 d). The resulting investigated range for OLR was from 8.9 to 45 $g_{VS}\ L^{-1}_{dig.}\ d^{-1}$. According to results of experiments conducted in previous work with a similar substrate [11], for FV the selected factors ranges were 27–72 $g_{VS}\ kg^{-1}_{ww}$ and 1–3 d for OMC and HRT, respectively, centerpoint of the design being (50 $g_{VS}\ kg^{-1}_{ww}$; 2 d). The corresponding range for the organic loading rate is approximately from 12.4 to 52.8 $g_{VS}\ L^{-1}\ d^{-1}$. All the coded levels and corresponding values of operating variables considered in the experimental design are summarized in Table 1.

All reactors were initially inoculated with a digested material collected in a 10 L laboratory-scale reactor, digesting a mixture of the four organic substrates used in this study. The digester had been continuously operating under thermophilic conditions (55 °C) for approximately 20 days, prior to the beginning of this study, showing a stable production of biohydrogen. The TS and VS concentrations and the pH of the inoculum resulted in 36.1 ± 4.3 g kg^{-1}_{ww}, 29.4 ± 3.6 g kg^{-1}_{ww} and 5.65 ± 0.23, respectively.

The test was prolonged for almost 10–15 days, till the production of biogas conditions was stable. The last 5 days of steady-state stable production were taken into account for data elaboration, for sampling the pre-digested materials and for analyses. This in order to avoid the start-up phase and any unstable/transitory condition. Biohydrogen production was calculated from volume measurements of gas accumulated in sample bags and by measuring its hydrogen content.

2.2. Methanogenic process (2nd stage and single-stage)

Optimized methanogenic process was applied to raw materials (simulating one-stage process) and to treated materials (simulating the second stage process). Only the most productive EC were chosen, i.e. those reaching hydrogen yield ($Sdm^3H_2\ kg^{-1}_{VS}$) above 30% of the most productive EC for each biomass type. Treated materials were sampled 4 different times from the hydrogenic reactors at steady state and mixed together in one single sample. Methanogenic assays were performed in triplicate for each EC.