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Development and pilot-scale validation of a fuzzy-logic control system for optimization of methane production in fixed-bed reactors

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ABSTRACT

The objective of this study was to develop an advanced control system for optimizing the performance of fixed-bed anaerobic reactors. The controller aimed at maximizing the bio-methane production whilst controlling the volatile fatty acids content in the effluent. For this purpose, a fuzzy-logic controller was developed, tuned and validated in an anaerobic fixed-bed reactor at pilot scale (350 L) treating raw winery wastewater. The results showed that the controller was able to adequately optimize the process performance, maximizing the methane production in terms of methane flow rate, resulting in an average methane yield of about 0.29 $L_{CH4}\,g^{-1}$ COD. On the other hand, the controller maintained the volatile fatty acids content in the effluent close to the established maximum limit (750 mg COD L^{-1}). The outcomes of this study are expected to facilitate plant engineers to establish an optimal control strategy that enables an adequate process performance with the maximum bio-methane productivity.

1. Introduction

Nowadays, a major issue to overcome in order to achieve a global sustainable development is our dependency on fossil fuels for electricity production, which represents up to 80% of the global energy consumption [1]. Therefore, one of the main challenges of this century is to develop new competitive sources of renewable energy, capable of replacing fossil fuels with a minimum impact on both environment and society [2]. In this context, alternative energy sources must be pursued [3]. Methane production from anaerobic digestion (AD) of waste represents a sustainable treatment strategy for waste valorisation. In addition, when the treated waste has a biological origin the bio-methane produced can be considered as a carbon neutral energy source due to its net balance of greenhouse gases emissions.

Due to the high methane productivities that can be achieved by high-rate anaerobic reactors, a huge effort is currently being put on the study of systems such as up-flow anaerobic sludge blanket (UASB), expanded granular sludge blanket (EGSB), anaerobic membrane bioreactor (AnMBR) or fixed-bed bioreactor [4]. In these reactors, the biomass is self-immobilized, allowing uncoupling the hydraulic retention time (HRT) and the solid retention time (SRT).

However, the complexity and the diversity of the phenomena ocurring in high-rate anaerobic reactors have delayed the understanding, and consequently the proper control, of this AD process. Due to the large number of factors that affect anaerobic processes, the selection of proper monitoring indicators and the development of advanced control systems are crucial for a successful optimization of the process performance [5,6].

Biogas composition and production rate are the most commonly used variables acting as indicators of the process performance during AD. In addition, the methane yield (Y_{CH4}), which is usually defined as the amount of methane produced per unit mass of organic matter removed, is also used as an indirect parameter for evaluating the performance of anaerobic processes [7,8].

Abbreviations: AD, anaerobic digestion; AnMBR, anaerobic membrane bioreactor; CT, conductivity-transmitter; EGSB, expanded granular sludge blanket; FIT, Flow-Indicator-Transmitter; GC, gas chromatograph; GCT, gas composition transmitter; HN, High Negative; HP, High Positive; HRT, hydraulic retention time; LN, Low Negative; LP, Low Positive; N, Negative; OLR, organic loading rate; P, Positive; PID, Proportional-Integral-Derivative; PIT, Pressure-Indicator-Transmitter; PLC, Programmable Logic Controller; SRT, solid retention time; TA, Titrimetric Analyzer; TT, temperature transmitter; UASB, up-flow anaerobic sludge blanket; VFA, volatile fatty acid; Z, Zero.

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Nomenclature

q_{CH4} Methane flow rate
$G_{CORRECTED}$ Corrected biogas flow
$G_{MEASURED}$ Measured biogas flow
frho Volumetric correction factor
rho_{AIR} Volumetric weight of air
rho_{CH4} Volumetric weight of CH_4
rho_{CO2} Volumetric weight of CO_2
rho_{N2} Volumetric weight of N_2
$eq_{CH4}(t)$ Error in methane flow rate at a given time
$q_{CH4}(t)$ Methane flow rate at a given time
$q_{CH4}{}^{*}$ 2-h moving average of $q_{CH4}(t)$
q_{CH4_SP} Set-point of methane flow rate
$\Delta eq_{CH4}(t)$ Variation in the error of the methane flow rate at a given time
$eq_{CH4}(t\text{-}1)$ Error in methane flow rate at the previous control action
δ Modifying algebraic factor
dVFA (t) Difference between VFA_{MAX} and the VFA content in the effluent at control time
VFA (t) Effluent VFA concentration at a given time
VFA * 2-h moving average of VFA (t)
VFA_{MAX} Maximum effluent VFA concentration
$\Sigma eq_{CH4}(t\text{-}1)$ Accumulated error in methane flow rate at the previous control action
Σeq_{CH4} Accumulated error in methane flow rate at a given time
p Numerical value of a variable
c Center of the gaussian-type membership function
$\mu(p)$ Degree of membership of the input variable p
σ Amplitude of the gaussian-type membership function
Δq_{CH4_SP} Modification in methane flow rate set-point
q_{IN_SP} Set-point of influent flow rate
Δq_{IN} Modification of the influent flow rate
Y_{CH4} Methane yield

Nevertheless, these indicators can be insufficient to evaluate the overall process performance. This is because they usually indicate too late disturbances affecting the process, when there is no possible action to recover it immediately. To avoid this issue, the concentration of volatile fatty acids (VFA) has been proved to be an adequate state indicator for monitoring AD processes [9]. VFAs are main intermediate metabolites in AD and therefore, monitoring their concentration can be a useful tool for process diagnosis (*e.g.* to detect AD imbalances). Moreover, as this variable can be easily on-line monitored, for instance by means of titrimetric sensors, it gives a much faster and more reliable information than other common indicators applied for AD monitoring, such as pH, alkalinity, gas composition or gas production [10–14].

Many different alternatives, such as classical Proportional-Integral-Derivative (PID) control, fuzzy systems, neuron networks or model-based systems, have been applied for controlling AD process [15]. Fuzzy-logic control has the main advantage of being applicable to control non-linear systems, such as AD. A fuzzy-logic controller [16] is able to optimize different types of processes under dynamic conditions by applying valuable expert knowledge [17–20]. Moreover, fuzzy-logic controllers do not require large amounts of data and/or rigorous mathematical models, thus allowing a much simpler calibration of the controller. In addition, these control systems allow the development of multiple-input-multiple-output control schemes. Hence, it can be stated that fuzzy logic is a powerful tool for controlling anaerobic fixed-film reactors [21]. Therefore, fuzzy-logic control has been widely implemented in wastewater treatment over the last decades and has been successfully featured in several AD applications [22–26]. As listed in Jimenez et al. [15], different applications of fuzzy-logic control systems for AD control can be found in the literature. Taking some examples, Puñal et al. [27] developed a PI-based fuzzy-logic controller which used the dilution rate as manipulated variable to control the concentration of VFAs in the effluent. In addition, Murnleitner et al. [28] applied fuzzy theory to avoid overloading of AD reactors. Recently, Robles et al. [29] demonstrated the suitability of fuzzy-logic systems for controlling the methane production in AD reactors using the methane flow rate and the VFA concentration as input variables. Nevertheless, only one study has been carried out so far for optimization of AD processes using fuzzy logic. Carlos-Hernandez et al. [30] proposed a fuzzy supervisory controller to optimize the AD performance by controlling alkali addition and the dilution rate. To the knowledge of the authors, no other study has been carried out to apply fuzzy-logic control systems for AD optimization.

Considering the aforementioned information, the main objective of this study was to develop an advanced control system for optimizing the methane production in fixed-bed anaerobic reactors. To this purpose, a fuzzy-logic system consisting of a supervisory controller to determine the set-point of methane flow rate and an upper-layer controller to define the inflow of substrate into the reactor was first developed by simulation and then validated in a 350 L pilot-scale fixed-bed anaerobic reactor treating industrial winery wastewater. The proposed controller aimed at maximizing bio-methane production whilst controlling the VFA concentration in the effluent. The main novelty of this study lies not only in developing a controller for optimizing the operation of fixed-bed anaerobic reactors, but also in its validation under specific conditions that were similar to those found in full-scale plants.

2. Materials and methods

2.1. Pilot plant description and operation

Fig. 1 shows the flow diagram and the instrumentation of the continuous fixed-bed anaerobic reactor used in this study. The plant had a total volume of 358 L. The support media (Cloisonyl: 180 $m^2\,m^{-3}$ specific surface) filled 34 L, leaving 324 L as effective volume. The anaerobic reactor was jacketed and connected to a water heating system for temperature control. Moreover, the plant was equipped with a pH control by feeding NaOH (30%) to the system when necessary. The pH set-point was set at 7.2.

The plant was fed with industrial winery wastewater from local cellars located in the area of Narbonne, France. Table 1 shows the main average characteristics of the influent wastewater during the experimental period. The industrial winery wastewater was stored in a 27-m^3 tank that was connected to a dilution system of 0.2 m^3 from which wastewater was fed to the pilot plant. The main aim of this dilution system was to allow testing different organic loading rates (OLRs) in the plant. In the reactor, a portion of the mixed liquor was recycled from the bottom to the top for both improving the mixing conditions and favouring the stripping of the produced

Table 1
Average raw wastewater characteristics.

Parameter	Unit	Mean ± SD
COD	g COD L^{-1}	21.6 ± 0.8
Acetate	g COD L^{-1}	3.7 ± 0.4
Propionate	g COD L^{-1}	4.6 ± 0.8
Butyrate	g COD L^{-1}	2.8 ± 0.3
Valerate	g COD L^{-1}	1.5 ± 0.7