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Design study of an AnSBBR for hydrogen production by co-digestion of whey with glycerin: Interaction effects of organic load, cycle time and feed strategy

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ABSTRACT

An anaerobic sequencing batch biofilm reactor (AnSBBR) treating a mixture of dairy industry wastewater and biodiesel production wastewater (co-digestion of whey with glycerin) was applied to hydrogen production. The influence of fed-batch and batch mode, cycle time and interactions effects between influent concentration and cycle time (2, 3 and 4 h) over the organic loading rate were assessed in order to obtain a sensitivity analysis for important operational variables to the reactor. It was possible to find an optimal cycle time of 3 h with an influent concentration of 7000 mgCOD L^{-1} (molar productivity 129.0 $molH_2\ m^{-3}\ d^{-1}$ and yield 5.4 $molH_2\ kgCOD^{-1}$). Reactor operation in fed-batch mode allowed higher hydrogen production rates. Increasing the influent concentration (with a constant cycle time) was better for the hydrogen production process than decreasing the cycle length (with a constant influent concentration), which means that these two parameters have different weights in the organic loading rate. The best operational conditions produce hydrogen via acetic, butyric and valeric acids similarly. The system is able to produce 1.3 kJ per gram of COD applied.

Introduction

There are several possibilities to design anaerobic digestion systems [28]. Several researchers have already reported a great number of reactor designs with their operational and performance parameters. The basic requirements for an anaerobic digester design are: to maximize the degradation of volatile solids and associated biogas yield; to allow for a continuously high and sustainable organic loading rate and a short hydraulic retention time to minimize reactor volume; to ensure thorough mixing with an effective transfer of organic material for the active microbial biomass; and to release gas bubbles trapped in the medium and to prevent sedimentation. Other requirements are the reduction of process energy and heat loss, odor control and finally, to achieve a reliable system

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with the lowest possible installation and operating cost [5,19,21].

There are various types of reactors in use today, and each design is related to the quality of the feedstock to be digested, with capital investment factors, and with the principal function of digestion. The different groups of reactor design commonly used for the anaerobic digestion (AD) are batch, continuous one-stage and continuous two-stage reactors, anaerobic sequencing batch reactor (ASBR), anaerobic sequencing batch biofilm reactors (AnSBBR), anaerobic filters (AF), plug flow reactor (PFR), up-flow anaerobic sequencing batch (UASB) reactor, anaerobic fluidized bed (AFB) reactor, and oscillatory flow reactor (OFR).

Batch reactors are the simplest. These are filled with the feedstock while the reaction is carried out and nothing else is introduced or withdrawn until the reaction is done. The major advantages of this type of operation are its simplicity, good effluent quality control and possibility of applying this kind of treatment in a wide range of wastewaters [21]. These anaerobic batch and fed-batch reactors have a typical cycle comprises of four steps: *(i)* feeding in which fill time may vary, defining the feed strategy as batch and/or fed batch; *(ii)* the treatment itself, by biotransformation of the wastewater constituents by microorganisms; *(iii)* sedimentation, when the biomass is in granular form (ASBR) because when the biomass is immobilized on inert support (AnSBBR) this step is not required; and *(iv)* discharge, i.e., removal of treated and clarified liquid [2,16,23]. New advancements in understanding the anaerobic sequencing batch and/or fed-batch reactor may still give rise to more options for its use and identify limits and drawbacks, among which should be mentioned: effect of using biomass immobilized on inert support; application to different types of wastewater; and the effect of feed strategy and organic loading rate over biogas production [16].

The main objective of this work is to assess the applicability of utilizing an anaerobic sequencing batch biofilm reactor with recirculation of the liquid phase that contains immobilized biomass (AnSBBR) for the co-digestion of whey and glycerin aiming to produce hydrogen. A design study of some operational parameters was performed: the influence of feeding mode (batch or fed-batch); cycle time (2, 3 or 4 h); and the interactions effects of influent concentration (4700, 7000 and 9300 mgCOD L^{-1}) and cycle time (2, 3 or 4 h) over the organic loading rate. The study was performed in order to obtain a sensitivity analysis for important operational variables of the reactor over hydrogen productivity and yield. With this analysis results, the energy recovery of the best experimental condition was calculated. In addition, a metabolic kinetic model was assessed to better understand the biological pathways of the system.

The justification for the choice of producing hydrogen is that it is considered to be a clean fuel because when combusted only water is released as the end product [10,13]. The use of whey as a source for hydrogen production is motivated by its large production (approximately 5 million tons per year) and even with the technological possibility of using this compound as a byproduct, this may not be economically feasible. This effluent has BOD and COD values ranging from 27–60 kg/m^3 and 50–102 kg/m^3, respectively, a low alkalinity content (<2500 mgCaCO_3 L^{-1}), high TKN content (up to 1700 mg L^{-1}) and very high biodegradability [4,20,24]. Glycerol is the major by-product of the biodiesel industry (approximately 100 kg of biodiesel produced 10 kg of crude glycerol) and the global biodiesel market is estimated to reach 37 billion gallons by 2016 with an average annual growth of 42%. Pure glycerol has applications in pharmaceutical, food, and cosmetic industries, but the refinement of crude glycerol to a high purity is too expensive, especially for small and medium biodiesel producers. Crude glycerol that is generated by homogeneous base-catalyzed transesterification contains approximately 50–60% glycerol, 12–16% alkalis, especially in the form of alkali soaps and hydroxides, 15–18% methyl esters, 8–12% methanol, and 2–3% water. In addition to methanol and soaps, crude glycerol also contains a variety of elements such as Ca, Mg, P, and S as well as other components [9,18,26].

Therefore, this design fits into the biorefinery concept, integrating biodiesel (glycerin) and dairy products (whey) production, energy recovery by treatment of the main waste produced by this industries and possibility of using the treated effluent in the process. Besides that, the addition of a co-substrate is a feasible option to overcome the drawbacks of monodigestion and to improve the economic feasibility of the process, because it dilutes toxic compounds, balances nutrients, encourages synergy between microorganisms and increases the biodegradable organic matter [1,29]. It is important to emphasize that the effluent of the acidogenic reactor proposed in this work should have a second treatment aiming to obtain energy recovery in the form of methane, as Ref. [17].

Material and methods

Anaerobic sequencing biofilm batch reactor (AnSBBR)

The system used for hydrogen production by anaerobic treatment from the co-digestion of whey with glycerin consisted of a reactor, which was an acrylic cylindrical column with a height of 540 mm, an external diameter of 100 mm and a wall thickness of 3.5 mm, and a recirculation unit which comprised: (i) a side reservoir that contained 1.5 L of liquid medium, consisting of a cylindrical acrylic container with a height of 300 mm, an external diameter of 100 mm and a wall thickness of 3.5 mm (total capacity of 2.1 L); and (ii) a diaphragm pump. The interstitial recirculation velocity was 0.2 cm s^{-1}. The total volume of the reaction medium (2.0 L contained in the reactor and 1.5 L in the side tank) was 3.5 L. The chamber in which the reactor was operated was kept at 30 ± 1 °C. A schematic of the system can be found in Fig. 1 and a photograph of the system is shown in Fig. 2.

Support for immobilization and inoculum

Low-density polyethylene (LDPE) was used as the support for the immobilization of the biomass. The particles were approximately 5 mm long by 3 mm in diameter, the porosity of the bed was calculated to be 43%. The inoculum came from an up-flow anaerobic sludge blanket reactor treating wastewater from a poultry slaughterhouse. A heat shock pretreatment

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