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Start-up and operation of continuous stirred-tank reactor for biohydrogen production from restaurant organic solid waste

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ABSTRACT

The hydrogen production from a variety of substrates, including organic solid waste (OSW), has been studied at different organic loading rate (OLR), finding different behavior on the hydrogen production rate (HPR) that can be related to the particular waste characteristics and particular operational conditions. The objective of this study was to evaluate the start-up and operation of a continuous stirred-tank reactor (CSTR) to generate hydrogen from food waste applying different OLR in order to determine the operational conditions to obtain the maximal HPR. Three OLR, controlled via the influent flow rate, were studied: 19, 38 and 57 $gVS/L_{reactor}/d$. It was found that the OLR has an influence on the hydrogen production in the CSTR. The increase of OLR results in a decrease of COD removal, protein removal, and hydrogen yield (YH_2). The highest HPR (19.8 mmol $H_2/L_{reactor}/d$) and YH_2 (0.6 mmol H_2/gVS) were obtained at the OLR of 37.1 and 19.8 $gVS/L_{reactor}/d$, respectively. The H_2 percentage in biogas had variations between 25 and 55% independently of the OLR. The VS and COD removal efficiencies were 51 ± 9% and 27 ± 9% respectively. Acetic acid was the principal VFA produced during the CSTR operation.

Introduction

Hydrogen (H_2) has been widely recognized as an alternative energy source to substitute fossils fuels. H_2 gas comprises a clean fuel with no carbon dioxide (CO_2) emissions and can easily be used in fuel cells for the generation of electricity [1]. The H_2 has a high energy yield of 122 kJ/g, which is 2.75 times greater than hydrocarbon fuels [1–4]. Among the H_2 production methods, the most promising and eco-friendly approach is dark fermentation from organic solid waste (OSW), especially food waste [2,5].

Dark fermentation is a biological process where a microbial consortium degrades the organic matter at anaerobic condition to produce biogas composed of H_2 and CO_2, and a digestate rich in volatile fatty acids that can be used in other biological processes such as photofermentation. Dark fermentation is a step intermediate in anaerobic digestion, which is performed in four stages: hydrolysis, fermentation, acetogenesis and methanogenesis [1]. H_2 is a key intermediate consumed mainly during the methanogenic stage. For this

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reason, the methanogenic microorganisms must be inhibited to obtain an efficient H_2 production. Methanogen inhibition is possible applying different strategies including biokinetic control (control of organic loading rate, pH, or hydraulic residence time) [6] and inoculum pretreatment, e.g., chemical, heat-shock treatment [7]. Heat-shock treatment has been used to inactivate methanogenic microorganisms and selecting H_2 production microorganisms as spore-forming bacteria such as *Clostridium* sp. [7].

It has been reported that food waste can be used as substrate to produce H_2 by dark fermentation in continuous and batch processes [1,6,7]. For the case of H_2 production in a continuous process, the continuous stirred-tank reactor (CSTR) has demonstrated a long-term operation and continuous H_2 production [7–10]. However, a frequent drawback is the process instability, that could be attributed to multiple reasons including the start-up of the reactor, inoculum and waste characteristics, and the operational parameters including the temperature, pH, and the organic loading rate (OLR), etc. [6,12–14]. The H_2 production in CSTR from OSW has been studied at different organic loading rate (OLR) [8–10]. It has been found that different OLR lead to different hydrogen production rate (HPR). For this reason, it becomes necessary to study the effect of OLR on the HPR in a continuous process.

The objective of this study was to evaluate the start-up and operation of a CSTR to generate H_2 from a restaurant food waste applying different OLR in order to determine the operational conditions which obtain the maximal HPR.

Materials and methods

Inoculum

Anaerobic granular sludge from an anaerobic sludge blanket reactor treating brewery wastewater was used as inoculum. The sludge was pretreated by a thermal shock at 105 °C for 24 h in order to inhibit the activity of methanogenic archaea and to select hydrolytic and fermentative bacteria (mainly related to microorganisms of genus *Clostridium*) [7]. After the thermal treatment, the material was broken up using a mortar, sieved through a # 20 mesh (850 μm) and stored in a sealed glass container at room temperature (24 ± 0.1 °C) until use, according to [15]. The physicochemical characteristics of the inoculum after the thermal pretreatment are shown in Table 1. The inoculum (10 g/L based on dry cell weight) used in the reactor start-up was activated during 48 h to degrade an easy-to-degrade medium (glucose) according to [7], in order to have a stable initial H_2 production activity.

Table 1 – Characteristic of the raw food waste and the pretreated inoculum.

Parameters	Food waste	Pretreated inoculum
Moisture (%)	75.7 ± 4.6	9.6 ± 0.0.3
TS (%)	24.3 ± 4.6	90.4 ± 0.02
VS (%)	20.8 ± 2.3	80.4 ± 0.02
COD (g/kg)	344.7 ± 35.3	1410 ± 70
Carbohydrates (g/kg)	59.6 ± 2.7	39.2 ± 4.5
Proteins (g/kg)	108.1 ± 8.3	276.7 ± 4.4
Density (kg/m^3)	1097.6 ± 29.7	–
pH	4.4 ± 0.01	–

Food waste feedstock

Food waste was obtained from a buffet-type restaurant in Querétaro City, Mexico. The restaurant food waste was considered generically as OSW in this study. Food waste was collected daily during seven days and stored at 4 °C. The physical composition of the food waste was as follows: flour derived waste (bread, tortilla, cookies, etc.) 30 ± 8%, citrus waste 22 ± 4%, fruits, and vegetables waste 17 ± 4%, meat waste 10 ± 3 and other material (bones, inert material, etc.) 21 ± 7%. In each sampling, the citrus waste, bones and inert material (paper and plastic) were discarded; the rest of the fermentable matter was preserved.

After food waste selection, it was crushed and homogenized in a 1HP grinder (JR, MJ22). Particle sizes less than 5 mm were later obtained in a sieve. Finally, food waste was frozen at −20 °C until it was used. The physicochemical characteristics of the food waste used in this study are shown in Table 1.

Experimental set-up and operation

The start-up of the CSTR for H_2 production was obtained in three phases: 1) inoculum activation with glucose, 2) acclimation of inoculum to H_2 production in a discontinuous process and 3) continuous operation. The inoculum was activated in a sequential batch reactor (SBR) under mesophilic conditions (35 °C) and stirred at 70 rpm for 48 h. The activation was carried out in a medium solution with the next composition per liter of water: 10 g of inoculum (dry basis), 5 g of glucose, 0.3 g of K_2HPO_3, 0.4 g of NH_4Cl, 0.02 g of MgCl, 0.0004 g of MnCl, 0.02 g of $Fe_2(SO_4)\cdot 7H_2O$, 0.002 of $CoCl_2\cdot 6H_2O$, 0.002 g of $Na_2MoO_4\cdot 2H_2O$, 0.002 g of H_3Bo_4, 0.002 g of $NiCl_2\cdot 7H_2O$ and 0.002 of ZnCl.

The inoculum activated with glucose, was acclimatized to the food waste (19 gVS/L) in SBR mode for two cycles of 24 h. The SBR reactor was operated under the following operating conditions: temperature 35 °C, pH 5.5, and stirred at 70 rpm. After the end of the second cycle of the SBR operation, the operation mode was switched to continuous operation as CSTR.

The CSTR was operated during 186 days. The operational conditions were the following: controlled temperature of 35 ± 0.4 °C, pH of 5.5 ± 0.3, stirring at 90 rpm, reaction volume of 1.7 L and a headspace of 0.6 L. Three OLR were studied: 19, 38 and 57 gVS/$L_{reactor}$/d, corresponding to HRT of 24, 12 and 8 h, respectively. The OLR was controlled via the influent flow rate.

The CSTR set-up is shown in Fig. 1. It consisted of one 2.3 L reactor with a working volume of 1.7 L. Food waste was added with a peristaltic pump (Cole Parmer System 7553-12) from a storage tank at 4 °C (avoiding a fermentation of OSW in the storage tank). The pH in the reactor was adjusted by an automatic pH controller (Black Stone BL931700). It was coupled to a low flow peristaltic pump (Marlow Watson 120U) that added sodium hydroxide (NaOH) 2 N when the pH dropped below 5.4 and stopped when the pH reached a 5.5 value. The temperature in the reactor was maintained at 37 °C via