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Sequential operation of a hybrid anaerobic reactor using a lignocellulosic biomass as biofilm support

Mohamed Ali Wahab [a,b], Frédéric Habouzit [b], Nicolas Bernet [b], Jean-Philippe Steyer [b], Naceur Jedidi [a], Renaud Escudié [b,*]

[a] University of Carthage, Water Research and Technologies Centre (CERTE), Wastewater Treatment Laboratory, Tunisia
[b] INRA, UR50, Laboratoire de Biotechnologie de l'Environnement, Avenue des Etangs, Narbonne F-11100, France

HIGHLIGHTS

- Hybrid anaerobic reactor operated sequentially to treat liquid and solid waste.
- Lignocellulosic biomass used as both carrier support and substrate.
- High treatment efficiency during fast start-up and restart-up phases.
- Acclimation phase depends of the soluble fraction of lignocellulosic support.
- During non-feeding period, biofilm conserved its biological activity.

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ABSTRACT

Agro-industries are facing many economic and environmental problems associated with seasonal generation of liquid and solid waste. In order to reduce treatment costs and to cope with seasonal variation, we have developed a hybrid anaerobic reactor operated sequentially by using lignocellulosic biomass (LB) as biofilm carrier support. Six LBs were tested to evaluate the treatment performance during a succession of two start-up periods, separated by a non-feeding period. After a short acclimation phase of several days, all the reactors succeeded in starting-up in less than 1 month to reach an organic loading rate of 25 $g_{COD}\ L^{-1}\ d^{-1}$. In addition, they restarted-up successfully in only 15 days after a 3 month non-feeding period, indicating that biofilms conserved their biological activities during this last phase. As a consequence, the use of LB as a biofilm support gives the potential to sustain seasonal variations of wastewater loads for industrial application.

1. Introduction

The agro-industries are considered as water and energy intensive consumers and their activities have been always associated with economic and environmental problems due to the generation of large amounts of wastewater and solid waste, in addition to the increase of their carbon footprint. Thus, agro-industries should focus on improving their energy efficiency, water use and waste management. Hence, in a world where water scarcity and climate change are a reality, actions to protect the environment and enhance renewable energy are mandatory for any type and size of industries.

The high biodegradability of agro-industries waste often justifies the use of conventional biological treatments. Among them, anaerobic digestion (AD) is the most adequate technology for the treatment of wastewaters with high organic carbon concentration. AD ensures the degradation of organic matter simultaneously into a valuable biogas composed of methane (CH_4) and carbon dioxide (CO_2) and into a nutrient-rich digestate with agronomic qualities (Karthikeyan and Visvanathan, 2012). A major limitation of AD process is the long duration and instability of their transition phases (starting, re-starting, organic load increase) because of the low growth rates of anaerobic microorganisms and their sensitivity to perturbations such as organic overloads (Arnaiz et al., 2003; Cresson et al., 2009; Escudié et al., 2011). Moreover, application of AD for the treatment of agro-industrial waste and wastewater is hindered by several limitations, such as the heterogeneity and the seasonal supply of waste, low biogas production rate and high

* Corresponding author. Tel.: +33 468425173.
E-mail address: escudie@supagro.inra.fr (R. Escudié).

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investment cost (Ren and Wang, 2004; Sasaki et al., 2009). Thus, it is of high interest to develop an AD reactor with low investment and operational costs that could ensure the treatment of both liquid and solid waste in one single reactor with high treatment efficiency and high methane yield. The operation of this reactor has to tolerate seasonal fluctuations and OLR perturbations that can happen in agro-industries over the year.

Anaerobic fixed bed reactors (AFBR) present a good potential for the treatment of wastewaters. In fact, they are known to obtain high solid retention times for high system efficiency and stability, with low hydraulic retention times for system economy. Furthermore, these processes are inherently stable and resistant to organic and hydraulic shock loadings (Zhao et al., 2013). AFBR performance is strongly depending on the nature of the support material (Habouzit et al., 2014). Different natural and artificial solid materials can be used as biofilm carriers. Commercial carrier elements which are usually made of polyethylene, polypropylene or polyurethane, are expensive, while natural carriers are essentially inorganic such as sand, gravel, pumice stone, porous glass beads and zeolite (Tarjányi-Szikora et al., 2013).

Natural lignocellulosic biomasses (LBs) can be an alternative to these inorganic or plastic support materials. LBs are abundant in agro-industries and represent the main part of the solid waste produced. They have low costs, while having high porosity, low specific gravity and higher bacterial adsorption/adhesion (Nabizadeh et al., 2008). The LBs are essentially composed of cellulose, hemicelluloses and lignin in different proportions. The variation of their chemical composition can influence the treatment performance and methane production of the reactor, especially during the start-up period which constitutes an important step in the anaerobic biological treatment process (Cresson et al., 2009; Habouzit et al., 2014). However, the efficiency of LB to be used as biofilm carrier has not been well studied. Andersson and Björnsson (2002) and Mshandete et al. (2008) have investigated the use of wheat straw and sisal fiber waste, respectively, as biofilm supports in methanogenic bioreactors digesting crop waste leachate, in a two-stage anaerobic digestion. To our knowledge, there is no study which has investigated the efficiency of LB for the treatment of high strength wastewater in one-stage reactor.

Moreover, because of the seasonal production of effluents in the agro-industries (Zhao et al., 2008), the reactor operation is seasonally unstable. In fact, when the process is not fed (*i.e.*, "inactivity" period), the biological activity of the biofilm is affected and the reactor becomes difficult to be restarted again: this sequential operation can lead to the low removal of organic matters or to a prolonged period of acclimation (Sowmeyan and Swaminathan, 2008). The use of LB as a biofilm support could be a very interesting solution to keep the biofilm biologically active during the inactivity period.

The main objective of this study was to explore the potential and performance of using LB as biofilm support and for the seasonal treatment of high strength wastewater. Since the start-up phase is a critical step in the process operation, we have first investigated the efficiency of using six LBs (having different chemical compositions and biodegradabilities) as biofilm support during this decisive period. These reactors were restarted after an inactivity period of 3 month in order to simulate a sequential operation of the process.

2. Methods

2.1. Characterization of lignocellulosic biomasses

Six LBs were used to investigate the efficiency of using natural materials as biofilm carrier supports. LBs used were: wheat straw (WS), sunflower stalk (SS), grape stalk (GS), cactus fiber (CF), luffa fiber (LF) and cypress cones (CC). These LBs were used without grinding or any other pretreatment.

The following methods were applied in order to identify their biochemical characteristics and their biodegradability. The Total Solid (TS) and Volatile Solid (VS) contents were measured as described previously by Motte et al. (2013). The distribution of lignocellulosic compounds (soluble compounds, cellulose, hemicelluloses and lignin) was estimated according to a Van Soest fractionation adapted by Motte et al. (2014). The LBs were firstly grinded and sieved to achieve a particle size of 1 mm.

Biomethane potential (BMP) of each LB was evaluated by following the methane produced under mesophilic conditions (35 °C). The inoculum was an industrial sludge sampled from a UASB (Upflow Anaerobic Sludge Blanket) process treating sugar factory effluent. The assays were conducted in triplicate in 600 mL sealed flask (working volume of 400 mL) according to the procedure described by Motte et al. (2013). The methane production is expressed under standard condition and accounts for the variation of the gas content in the headspace of the reactors.

The biochemical composition and the biomethane potentials of the six LBs are reported in Table 1.

2.2. Laboratory-scale reactors

2.2.1. Experimental set-up

The anaerobic fixed bed reactor employed in this study is a PVC column with an internal diameter of 0.20 m and a height of 0.56 m. The total and working volume of the reactor were 16.7 L and 14.8 L, respectively. The reactor was equipped with hot water jackets to maintain a mesophilic temperature of 35 °C. Six reactors were packed with the different LBs used as carrier supports for biomass immobilization and retention. The influent was pumped to the top of the reactor by means of a peristaltic pump. The reactor liquid was recirculated within the reactor by means of a recirculation pump fixed at the bottom inside the reactor. The effluent was discharged at the top through a U-tube for separation of gas. pH was measured in the liquid outlet with a Mettler Toledo 1100 Calimatic pH meter, regulated at 6.8 by automatic NaOH addition. Biogas produced passed through a moisture trap and then to a milligas counter fitted with a 4–20 mA output (Ritter, Bochum, Germany).

2.2.2. Influent preparation and reactor inoculation

The influent was a wine-based reconstituted wastewater, complemented with nitrogen as NH_4Cl and phosphorus as NaH_2PO_4, in a ratio of COD/N/P equal to 400/7/1 (Cresson et al., 2009). The influent was daily prepared by diluting wine to different final COD concentrations ranging from 0.5 to 24 g L^{-1}. The reactor was inoculated with 1 g_{VS} L^{-1} of sludge originating from a large-scale anaerobic reactor treating distillery vinasse.

Table 1
Van soest fractionation, TS, VS content and biochemical methane potential of the six LBs.

Supports	LF	CC	GS	SS	WS	CF
TS (%)	90	82	79	92	94	89
VS (%TS)	89	77	74	83	87	84
Soluble fraction (%TS)	19.2	17.7	32.3	26.8	23	16.6
Hemicellulose (%TS)	24	16.3	15	14.2	23.8	23
Cellulose (%TS)	46	37	27.5	31.3	31.7	45
Lignin (%TS)	10.8	29	25.2	26.7	20.5	15.4
BMP (mL $_{CH4}$/g $_{VS}$)	434.11	68.18	220.93	325.22	347.95	281.71