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Development of a submerged anaerobic membrane bioreactor for concurrent extraction of volatile fatty acids and biohydrogen production

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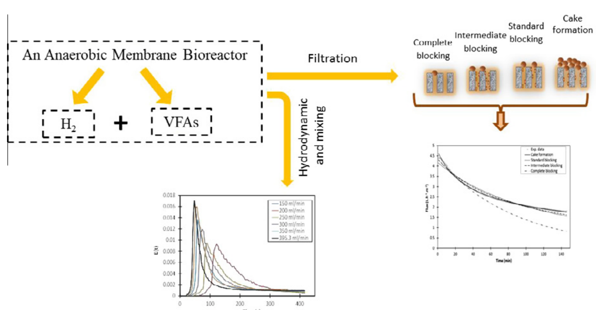
HIGHLIGHTS

- An externally-submerged anaerobic membrane reactor was used to produce $BioH_2$.
- Mixing, transmembrane pressure (TMP) and fouling were investigated.
- TMP was low (10 kPa) and fouling was reversible, mainly due to cake layer formation.
- Gas scouring and backwashing with the substrate were used as a cleaning procedure.
- Biohydrogen production was shown to restart after removing VFA in the permeate.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this work was to study an externally-submerged membrane bioreactor for the cyclic extraction of volatile fatty acids (VFAs) during anaerobic fermentation, combining the advantages of submerged and external technologies for enhancing biohydrogen ($BioH_2$) production from agrowaste. Mixing and transmembrane pressure (TMP) across a hollow fiber membrane placed in a recirculation loop coupled to a stirred tank were investigated, so that the loop did not significantly modify the hydrodynamic properties in the tank. The fouling mechanism, due to cake layer formation, was reversible. A cleaning procedure based on gas scouring and backwashing with the substrate was defined. Low TMP, 10^4 Pa, was required to achieve a $3\ L\ h^{-1}\ m^{-2}$ critical flux. During fermentation, $BioH_2$ production was shown to restart after removing VFAs with the permeate, so as to enhance simultaneously $BioH_2$ production and the recovery of VFAs as platform molecules.

1. Introduction

The benefits of biohydrogen ($BioH_2$) production through dark fermentation process regarding reduction in greenhouse gas emission and valorization of organic waste materials cannot be downplayed. However, low yield and production rate of $BioH_2$ have been the major barriers to the commercial-scale application of the

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List of abbreviations

AnSMBR	anaerobic submerged membrane reactor
CSTR	continuous stirred tank reactor
RTD	residence time distribution
TMP	transmembrane pressure (Pa)
VFAs	volatile fatty acids
A	membrane surface area (m^2)
$C(t)$	normalized concentration (-)
$E(t)$	residence time function (-)
$E(\theta)$	normalized residence function (-)
g	gravitational acceleration ($m\ s^{-2}$)
h	height (m)
h_{in}	inlet fiber height (m)
h_{out}	outlet fiber height (m)
J	permeate flux ($L\ h^{-1}\ m^{-2}$)
J_{pred}	predicted permeate flux ($L\ h^{-1}\ m^{-2}$)
J_0	initial value of the flux ($L\ h^{-1}\ m^{-2}$)
k	kinetic parameter of fouling (model-dependent unit)
k_a	complete blocking parameter (s^{-1})
k_b	standard blocking parameter ($s^{1/2}$)
k_c	intermediate blocking parameter (m^{-1}]
k_d	cake formation parameter ($s\ m^{-2}$)
L_{p_0}	water permeability ($L\ h^{-1}\ m^{-2}\ bar^{-1}$)
n	blocking index
P_{in}	inlet pressure (Pa)
P_{diff}	differential pressure (Pa)
P_f	feed pressure (Pa)
P_{out}	outlet pressure (Pa)
P_p	permeate pressure (Pa)
P_r	retentate pressure (Pa]
R_{ef}	external fouling resistance (m^{-1})
R_{if}	internal fouling resistance (m^{-1})
R_m	clean membrane resistance (m^{-1})
R_T	total membrane resistance (m^{-1})
t	time (s)
t_c	circulation time (s)
t_m	mixing time (s)
v	fluid velocity ($m\ s^{-1}$)
V	filtrate volume (m^3)
θ	normalized time (–)
μ	water viscosity (Pa s)
ρ	liquid density ($kg\ m^{-3}$)
σ_2	variance of the error of the flux model ($L^2\ h^{-2}\ m^{-4}$)
τ	space time in the membrane module (s)

dark fermentation process. Among the contributing factors to low $BioH_2$ yield is the accumulation of volatile fatty acids (VFAs), which results in a decrease in pH and consequent inhibition of the fermentation process. VFAs, including acetic, propionic and butyric acids, are usually produced through the main mechanism of the dark fermentation process, while other organic acids, such as succinic, lactic and fumaric acids are produced when there is imbalance during the digestion process. Therefore, regulation of VFAs production by continuously removing them from the fermentation medium is crucial for the process stability and efficiency. Meanwhile, extracted VFAs from fermentation medium can be used for the production of fuels and energy through biochemical of thermochemical pathways. The VFAs can also find a direct usage as food additives in the food and the pharmaceutical industries (Venkata-Mohan and Pandey, 2013). Different techniques including ion exchange (Gluszcz et al., 2004), adsorption (Joglekar et al., 2006), electrodialysis (Huang et al., 2007; Wang et al., 2006), liquid-liquid extraction (Mostafa, 1999; Senol and Dramur, 2004), distillation (Mumtaz et al., 2008), esterification (Pereira et al., 2011), reactive extraction (Hong et al., 2001) and membrane process (Wodaki and Nowaczyk, 1997) have been employed to recover organic acids from fermentation broth. Among the various techniques for VFAs recovery, membrane processes seem to be the most efficient, eco-friendly and economic method. Membrane filtration exhibits numerous benefits including small footprint, and enhanced retention which enables sludge retention time to be independently controlled from hydraulic retention time. It also reduces the additional cost of disinfectant since it allows the removal of microorganisms from VFAs to a certain degree for subsequent treatment.

Generally, the efficiency and economics of membrane filtration depend on membrane module design (tubular, plate and frame, rotary disk or hollow fiber), pore size (microfiltration, ultrafiltration, nanofiltration or reverse osmosis), membrane material (organic, inorganic, metallic, hydrophobicity or hydrophilicity), filtration mode (dead end or cross mode), operating conditions (flux, hydraulic retention time and sludge retention time) and sludge characteristics (biomass concentration, pH, extracellular polymeric substances and soluble microbial product). As a result, many challenges are associated with the application of membrane filtration process, among which the most important is membrane fouling. Membrane fouling is caused by particles deposition, plugging and narrowing of membrane pores and surfaces (Bae and Tak, 2005; Defrance et al., 2000). Flux and, hence, filtration efficiency is directly affected by membrane fouling with a consequent decrease in system productivity and increase in operating cost. Darcy's law highlights that the permeate flux through a porous membrane is directly proportional to the transmembrane pressure (TMP) and the membrane area, but is inversely proportional to the membrane resistance due to fouling and to feed viscosity, as shown in Eq. (1) (Field et al., 1995). In this equation, J is the permeate flux, μ the viscosity of the liquid feed; TMP and R_T, the transmembrane pressure and the total resistance, are given by Eqs. (2) and (3).

$$J = \frac{\mathrm{TMP}}{\mu R_T} \quad (1)$$

$$\mathrm{TMP} = \frac{P_f + P_r}{2} - P_p \quad (2)$$

$$R_T = R_m + R_{ef} + R_{if} \quad (3)$$

In the above equations, P_f, P_r, P_p, R_m, R_{ef} and R_{if} are the feed, retentate and permeate pressures, the clean membrane resistance, and the external and internal fouling resistance, respectively. As illustrated in Eq. (1), the rate of membrane fouling could be reduced by carrying out filtration process below the critical flux, and by maintaining simultaneously high shear rate through velocity gradient or gas sparging close to the membrane. Membrane fouling can also be reduced by using appropriate membrane configuration and modules, as in the case of hollow fiber membrane modules which constitute a common membrane configuration employed in many industrial membrane processes owing to its excellent mass transfer qualities and high membrane surface area.

Among the two main membrane configurations including submerged and side-stream membrane bioreactors (MBRs), internally-submerged MBR is usually preferred to side-stream MBRs owing to its advantages which include smaller footprint and less energy requirement (Cote et al., 1997; Singhania et al., 2012). However, in some commercial applications, side-stream MBRs were selected when a higher frequency for membrane