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Dynamic membrane-assisted fermentation of food wastes for enhancing lactic acid production

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HIGHLIGHTS

- Fermenter was stably operated under acidic conditions for LA production.
- DM could significantly intercept particles and enhance LA yield.
- High abundance of *Lactobacillus* dominated at uncontrolled pH and pH 4.
- Backwashing could effectively maintain the DM permeability.

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ABSTRACT

A dynamic membrane (DM) module was inserted into a fermentation reactor to separate soluble products from the fermented mixture to increase lactic acid (LA) production from food wastes under acidogenic conditions (uncontrolled pH, pH 4 and 5). With a high total suspended solid content (20–40 g/L) in the fermenter, a stable DM could be maintained through regular backwashing. By effectively intercepting suspended solids and lactic acid bacteria (LAB), the fermenter was able to increase microbial activity and largely promote LA yield. Hydrolysis and acidogenesis rates increased with pH, and the highest LA yield (as high as 0.57 g/g-TS) was obtained at pH 4. The microbial community analysis showed that the relative abundance of *Lactobacillus* increased to 96.4% at pH 4, but decreased to 43.3% at pH 5. In addition, the DM could be easily recovered by intercepting larger particles in less than 2 h after each cycle of periodic backwashing.

1. Introduction

Lactic acid (LA) is widely used in food, pharmaceutical, and cosmetic industries and has recently been highlighted as a raw material for polylactic acid (PLA) (Lasprilla et al., 2012; Dusselier et al., 2013; Dreschke et al., 2015). The continuous increase in demand for LA has led to rapid growth rate of the global market (Dusselier et al., 2013; Dreschke et al., 2015). Chemical synthesis and fermentation are the commonly used LA production methods, but the fermentation process is more attractive because it uses renewable materials and produces optically pure LA (John et al., 2009). Additionally, due to its large quantity and high organic content, food waste has become one of the main solid wastes in cities (Tang et al., 2016; Wu et al., 2015). Although LA fermentation from food waste has been reported in a number of studies (Tang et al., 2016; Ye et al., 2008), further investigations are required to improve the LA yield.

The conventional batch or continuous LA fermenters are widely used due to their high LA yield and stable operation (Wu et al., 2015; Liang et al., 2014). However, they have several drawbacks: first, they are not suitable for high concentrations of substrate because of their negative effect on the growth of lactic acid bacteria (LAB) (John et al., 2009; Tang et al., 2016); second, the feedback inhibition caused by accumulated free acids may restrict the bacterial activity and decrease the LA yield (Gao et al., 2011); third, substrates cannot be completely utilized and may retain at high levels

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in the effluent (Liu et al., 2016); and finally, LAB in the fermenter cannot accumulate to increase the population or accelerate the LA productivity. To improve the LA yield, fermentation conditions such as pH, organic loading rate (OLR), temperature, and types of inocula should be optimized (Tang et al., 2016; Wu et al., 2015; Liang et al., 2014). Continuous removal of LA with adsorption and ion exchange to counteract the negative effects caused by the accumulated end-products has been investigated in previous studies (Pal et al., 2009; Gao et al., 2011; Cui et al., 2016). Although these methods could improve the LA yield to some extent, they are usually costly and the down-stream processes may become complicated (Gao et al., 2011).

The utilization of membranes has appeared to be an option for solving the aforementioned problems because it can effectively separate the LA product from the fermenter to relieve the negative effect on further LA fermentation, intercept the particulate substrates to promote LA yield, and retain LAB to increase LA productivity (Pal et al., 2009; Zhao et al., 2010). Many efforts have been made to integrate membrane separation with LA fermentation (Wee et al., 2006; Mimitsuka et al., 2014). However, the high capital cost and short lifetime of the membrane unit often become the bottleneck problem to restrict low-cost production of LA. Therefore, it is required to establish a new fermentation system with low-cost membrane material.

Recently, the dynamic membrane bioreactors (DMBR), either operated aerobically (Wang et al., 2015; Ersahin et al., 2013) or anaerobically (Ersahin et al., 2016; Alibardi et al., 2014) have been studied as alternatives of conventional MBR, and showed their advantages of low-cost membrane module, high permeate fluxes (Ersahin et al., 2012; Chu et al., 2014; Hu et al., 2016). By intercepting suspended particles (e.g. sludge flocs and microbial cells) on a support material (e.g. nylon mesh and stainless steel mesh), a cake layer was formed, by which the solid particles were retained and only the soluble matter could pass through the membrane (Ersahin et al., 2012; Hu et al., 2016). Alibardi et al. (2016) succeeded in establishing an anaerobic DMBR with a large pore size mesh (200 μm) for wastewater treatment and achieved high organics removal under low transmembrane pressure (TMP). Recently, Liu et al. (2016) integrated an anaerobic digester into DMBR to produce volatile fatty acids (VFAs) and found that the system could enrich the functional bacteria, enhance enzymatic activities, and further improve the VFAs yield.

The application of DMBR in wastewater treatment and anaerobic digestion processes has indicated the applicability of low-cost membranes to assist waste disposal and resource recovery. However, little has been known about the feasibility of LA fermentation assisted by dynamic membrane (DM). It thus became the objective of this study to establish a DM fermenter for enhancing LA production from food wastes under acidogenic conditions. Attention was paid to the performance and LA yield of the DM fermenter under varied pH conditions, as well as the stability of the DM layer in long-term operation.

2. Methods and materials

2.1. Food waste substrate

The fresh food waste was collected from a university canteen in Xi'an, China. It mainly consists of rice, vegetables, and meat. The pretreatment procedures followed the ones described in our previous study (Tang et al., 2016). Briefly, food waste was homogenized with an electrical blender after animal bones and clamshells were separated and grease was removed. The resulting slurry was sieved (1 mm) and stored in a refrigerator (4 °C). Before adding the slurry into the reactors, the TS content of the fresh food waste slurry was adjusted to approximately 3% with tap water. The characteristics of the food waste slurry are shown in Table 1.

2.2. DM-assisted fermenter

The lab-scale DM assisted fermenter with a working volume of 25 L is shown in Fig. 1. A nylon mesh with an equivalent aperture of 50 μm and an effective filtration area of 0.04 m^2 was used as a support material for DM formation (Fig. S1, Supporting information). Two agitators (200 rpm) were installed beside the membrane module to continuously mix the fermentation broth and scrub the membrane to relieve the membrane fouling. The effluent was withdrawn continuously under a hydraulic head of merely 10 cm between the bioreactor and the effluent port. With the attachment of the particles on the mesh support, a cake layer was formed and acted as a DM filter. As the filtration continued, the DM layer might become compacted, resulting in a decrease in the membrane flux. When the membrane flux dropped to the prescribed value of 2.0 $L/m^2 \cdot h$, backwashing was conducted using the effluent (200 mL) to remove the foulants on the mesh support module and recover the membrane flux. The pH of the fermentation broth was continuously recorded with an on-line pH meter and automatically adjusted by adding NaOH or HCl (5 M) to the prescribed value except for the pH uncontrolled condition. A water bath was equipped to maintain the temperature of the broth at 37 °C. All devices were controlled by a program logical controller (PLC).

2.3. Operation of the fermenter

At the beginning of the experiment, the reactor was filled with 25-L food waste substrates (described in Section 2.1) and initiated. The indigenous microorganisms in fresh food waste were used as the starters as discussed in our previous study (Tang et al., 2016). During the first eleven days, the reactor was operated as a continuous stirring tank reactor (CSTR) with the hydraulic retention time (HRT) of seven days as a start-up stage at uncontrolled pH (pH = un). When the products in the effluent became stable, a nylon mesh support module was inserted into the reactor to start the DM assisted fermentation process. To investigate the effect of pH on LA fermentation and membrane performance, the fermenter was operated in three stages with different pH values, namely, uncontrolled pH (Stage 1) followed by pH 4 (Stage 2) and pH 5 (Stage 3). Hydraulic retention time (HRT) of the reactor varied between 7 and 10 d depending on the membrane flux; the solid retention time (SRT) was controlled at 30 d during the entire fermentation period by daily discharge of the broth from the reactor.

2.4. Analytical methods

2.4.1. Chemical analysis

Immediately after collecting the mixture and effluent from the fermenter, chemical analyses were conducted regarding the total chemical oxygen demand (TCOD), total nitrogen, total

Table 1
Characteristics of the food waste slurry.

Parameter	Units	Average	S.D.
pH	–	4.5	0.1
Total solid content (TS)	% of wet weight	3.0	0.5
VS/TS	%	90.4	10.8
Total COD (TCOD)	g/L	33.9	3.7
Soluble COD (SCOD)	g/L	12.1	0.4
Total carbohydrate	g/L	18.4	2.1
Total protein	g/L	3.6	1.5

Note: S.D. represents standard deviation.