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Optimization of volatile fatty acid production with co-substrate of food wastes and dewatered excess sludge using response surface methodology

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ABSTRACT

Central-composite design (CCD) and response surface methodology (RSM) were used to optimize the parameters of volatile fatty acid (VFA) production from food wastes and dewatered excess sludge in a semi-continuous process. The effects of four variables (food wastes composition in the co-substrate of food wastes and excess sludge, hydraulic retention time (HRT), organic loading rate (OLR), and pH) on acidogenesis were evaluated individually and interactively. The optimum condition derived via RSM was food wastes composition, 88.03%; HRT, 8.92 days; OLR, 8.31 g VSS/l d; and pH 6.99. The experimental VFA concentration was 29,099 mg/l under this optimum condition, which was well in agreement with the predicted value of 28,000 mg/l.

1. Introduction

Food wastes are the main source of decay, odor, toxic gas emission, and groundwater contamination due to their high volatile solids and moisture content. These wastes also have the potential to generate energy due to their higher organic composition and easily biodegradable nature. Anaerobic acidogenesis is an alternative strategy for treating food wastes because valuable products such as volatile fatty acid (VFA) can be harvested (Kim et al., 2006; Lim et al., 2008a,b), which makes the process more economical and environmentally sustainable. VFA resulting from acidogenesis can be used as energy and carbon sources for biological nitrogen removal (Lim et al., 2006, 2008a,b) and for biodegradable polyhydroxyalkanoate (PHA) storage (Yu, 2001; Kasemsap and Wantawin, 2007). In addition, VFA derived from acidogenesis of waste organic matter are highly suitable substrates for PHA production. This can substantially reduce the cost of PHA, as almost 40–50% of the total PHA production cost is attributed to the carbon source used (Van Wegen et al., 1998).

Residual activated sludge is characterized by a high content of organic compounds. Handling, treatment, and ultimate disposal of the excess sludge accounts for 40–60% of the total operational costs of an activated sludge treatment plant (Liu, 2003). The co-digestion of food wastes and excess sludge is especially attractive, representing an economical and feasible approach to improve conventional digesters. This is because co-digestion could dilute potential toxic compounds, improve the balance of nutrients and produce synergistic effects on microorganisms, which would lead to enhanced biogas production and biogas yields (Kim et al., 2004; Zhu et al., 2008; Li et al., 2008; Lee et al., 2009). Fermentation of VFA using food wastes and excess sludge as co-substrates is gaining importance and opening up new avenues for utilization of these renewable energy sources. Substrate concentration, hydraulic retention time (HRT), organic loading rate (OLR), temperature, and pH have all emerged as critical variables for enhancement of VFA production from organic acidogenesis (Rincon et al., 2008; Lim et al., 2008a,b; Feng et al., 2009; Jeong et al., 2009; Yuan et al., 2009).

The traditional approach of "one variable at a time" for optimizing VFA production from organic wastes is well accepted. However, the technique of "one variable at a time" is not able to evaluate the interactive effect of different factors on the results and it is also time and labor intensive. Therefore, an alternative strategy involving a statistical approach, e.g., factorial experimental design and response surface methodology (RSM) should be adopted to solve this complexity. RSM is a statistical tool that stems from experimental design and that was later introduced into numerical simulation in reliability assessment of complex multivariable systems (Yu et al., 2006). RSM provides a systematic and efficient research strategy for studying the interaction of various parameters effect using statistical methods. It has been extensively applied in microbial fields in recent years (Wang et al., 2005; Chen et al., 2009).

The main objective of this work was to investigate the individual and interactive effects of food wastes composition in a co-substrate (food wastes and dewatered excess sludge), based on volatile

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suspended solids (VSS), HRT, OLR and pH, on the VFA production from anaerobic acidogenesis during a semi-continuous process. A central-composite design (CCD) for four independent variables (food waste composition in co-substrate, HRT, OLR and pH), each at five levels, was used to design the experiment. According the results of CCD, 30 experiments with 16 cubic points and eight axial points and six replicates at the center point were required for this procedure. The concentrations of VFA, including acetate, propionate, butyrate, i-butyrate, valerate, were determined during each experimental procedure. The VFA values of steady state of each experiment were employed to optimize the parameter of VFA production from the co-substrate of food wastes and dewatered excess sludge during a semi-continuous process by RSM.

2. Methods

2.1. Inoculums and substrates

The seed sludge used for the acidogenic fermentation was collected from an anaerobic digester at the Sibao municipal wastewater treatment plant in Hangzhou. The concentrations of total solids (TS) and volatile suspended solids (VSS) in the sludge were 18.32 ± 0.1 and 10.70 ± 0.1 g/l, respectively. The artificial food wastes consisted of 11 types of food (%, w/w); including cabbage 17%, banana peels 8.5%, orange peels 10%, sponge gourds 5%, peals 7%, apples 8.5%, celery 5%, noodles 8.0%, boiled rice 9%, potatoes 17% and carrots 5%. The food wastes were crushed with an electric blender and diluted to TS (%, w/w) 13.4 ± 2.0 and VSS (%, TS) 94.7 ± 2.0 with tap water. The dewatered excess sludge was obtained from Sibao municipal wastewater treatment plant with TS 23.4 ± 1.6% and VSS 45.0 ± 2.0%, respectively.

2.2. Reactor and operation

A 500 ml serum bottle was used as a reactor in this study and operated in semi-continuous mode (once-a-day draw-off and feeding), and 200 ml seed sludge was added to the bottle. The mixture of food wastes and dewatered excess sludge was taken as the substrate. The pH in each reactor was adjusted by adding 3 M NaOH or 3 M HCl after feeding everyday. Subsequently, each bottle was flushed with N_2 gas for 2 min and sealed tightly with a rubber plug linked to a silicone gas release tube. The bottles then were placed in a reciprocating shaker with 160 rpm at 35 °C. The HRT was equal to the solid retention time (SRT) in the experiment because solid was withdrawn with the mixed liquor everyday.

Reactors were considered to be in a steady state when the concentrations of soluble chemical oxygen demand (SCOD) and VFA in the effluents were stable. Steady state was usually achieved within 4 h of HRT, but experiments were conducted for 5–6 h HRT to ensure steady-state conditions (Lim et al., 2008a,b).

2.3. Analytical techniques

All samples were analyzed after centrifugation at 10,000 rpm for 10 min and filtrated through a 0.45 μm membrane. The analyses of PO_4^{3-}—P, NH_4^+—N, pH, TS and VSS were conducted in accordance with standard methods (APHA, 1995). VFA concentrations were the sum of various acids, which was expressed as chemical oxygen demand (COD) by using appropriate conversion factors as 1.067 for acetic acid; 1.514 for propionic acid; 1.818 for butyric and i-butyric acids and 2.039 for valeric and i-valeric acids. The acids were determined by a gas chromatograph (GC) (Lunan, SP-6890) equipped with a flame ionization detector (FID) and a 2 m × 4 mm column (GDX-103) using nitrogen as carrier gas. The temperatures of the injector, column and detector were 220 °C, 195 °C and 220 °C, respectively. The samples were first acidified by formic acid to adjust the pH to approximately 2.0 before the VFA were analyzed. The final data were the average of samples of three continuous reactor runs in steady-state conditions.

2.4. Experimental design

A central-composite design (CCD) for four independent variables, each at five levels, was used to fit a second-order polynomial model. This indicated that 30 experiments with 16 cubic points and eight axial points and six replicates at the center point were required for this procedure. The software Design Expert Version 7.1.2®, Stat-Ease Inc. Minneapolis, USA was used to design the experiment. The variables of food wastes composition in the co-substrate, based on VSS, HRT, OLR and pH values, and their levels are shown in Table 1. Table 2 shows the experimental design with parameters in coded and actual terms.

2.5. Statistical analysis

The VFA concentration was the dependent output variable. The experimental data obtained from the design were analyzed by the

Table 1
Levels of factors used for process optimization of VFA production.

	Variable name	Level				
		−2	−1	0	1	2
A	Food wastes composition(%,VSS basis)	80	85	90	95	100
B	HRT (day)	4	6	8	10	12
C	OLR (g VSS/l d)	4	6	8	10	12
D	pH	5.5	6.0	6.5	7.0	7.5

Table 2
Central-composite design of independent variables for process optimization.

Run	Coded				Actual			
	A	*B*	*C*	*D*	*A*	*B*	*C*	*D*
1	1	1	1	−1	95	10	10	6
2	−1	−1	−1	−1	85	6	6	6
3	1	1	1	1	95	10	10	7
4	1	1	−1	1	95	10	6	7
5	1	−1	−1	−1	95	6	6	6
6	−1	−1	1	1	85	6	10	7
7	0	0	0	0	90	8	8	6.5
8	−1	1	1	−1	85	10	10	6
9	0	0	−2	0	90	8	4	6.5
10	−1	1	−1	1	85	10	6	7
11	0	0	0	0	90	8	8	6.5
12	−1	1	−1	−1	85	10	6	6
13	0	0	0	0	90	8	8	6.5
14	1	−1	−1	1	95	6	6	7
15	1	−1	1	−1	95	6	10	6
16	1	−1	1	1	95	6	10	7
17	0	0	0	2	90	8	8	7.5
18	−1	−1	−1	1	85	6	6	7
19	−1	1	1	1	85	10	10	7
20	0	0	0	0	90	8	8	6.5
21	2	0	0	0	100	8	8	6.5
22	0	0	0	0	90	8	8	6.5
23	1	1	−1	−1	95	10	6	6
24	−2	0	0	0	80	8	8	6.5
25	0	0	2	0	90	8	12	6.5
26	0	0	0	0	90	8	8	6.5
27	0	−2	0	0	90	4	8	6.5
28	−1	−1	1	−1	85	6	10	6
29	0	2	0	0	90	12	8	6.5
30	0	0	0	−2	90	8	8	5.5

A, food wastes composition (%, VSS basis); *B*, HRT (day); *C*, OLR (g VSS/l d); *D*, pH.