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Optimization of process parameters for anaerobic fermentation of corn stalk based on least squares support vector machine

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ABSTRACT

In order to improve the yield and efficiency of biogas produced from anaerobic fermentation of corn stalk, least squares support vector machine (LS-SVM) was used to optimize the pretreatment process parameters. Weight of corn stalk, ultrasonic duration time, alkali pretreatment (2% NaOH) time, and single/dual-frequency ultrasound were selected as the experimental factors of orthogonal experimental design (OED). A new modeling method combining LS-SVM and OED was proposed to establish the predictive model between cumulative biogas production (CBP) and pretreatment process parameters. The effect of experimental factors on CBP was analyzed by two-dimensional (2D) and three-dimensional (3D) contour maps of the predictive model. The optimum parameters for process pretreatment were as follows: weight of corn stalk 53 g, dual-frequency ultrasound, ultrasonic duration time 33 min, alkali pretreatment time 56 h. The CBP of the optimal conditions obtained was 22.69 L and was 14.13% higher than that of optimal conditions for OED.

1. Introduction

Corn stalk is an important byproduct of agriculture, and reasonable applications of the corn stalk not only can avoid the environmental problems caused by unreasonable treatment (such as combustion), but also can convert the biological energy of stalk into clean energy (Liu et al., 2017). Anaerobic digestion to produce biogas is an effective way to transform the stalk energy (Yuan et al., 2011; Gao et al., 2017; Mustafa et al., 2017). Stalk is usually difficult to be used directly by anaerobic microorganisms due to its complex structure, so it is necessary to pretreat the stalk in order to improve the efficiency of anaerobic fermentation (Cai et al., 2016; Liu, et al., 2017; Zheng, et al., 2014). The usual pretreatment methods are chemical pretreatment, physical pretreatment, biological pretreatment as well as combined pretreatment method. Alkaline pretreatment destroyed the structure of lignin and weakened the interaction between cellulose and hemicelluloses, which increased porosity and internal surface area, and reduced the degree of polymerization and crystallinity. Yang et al. (2003) compared the pretreatment effect of NaOH, ammonia, urea and fungi on the corn stalk, which showed that the biogas yield of the stalk treated by NaOH was significantly higher than that of the untreated and bio-pretreated stalk. However, high concentration of chemical reagents may cause recontamination of the environment. Physical pretreatment, such as steam-explosion method, used high-pressure steam for a short time to degrade the pretreated biomass without adding any chemicals (Xu et al., 2012), thus the method requires higher energy input. The biological pretreatment method does not add chemicals and require only a low energy input (Guo et al., 2011), but the pretreatment time is longer, which limits the use of the method. The single-frequency ultrasound combined with alkaline pretreatment enhanced the effect of chemical method because the strong impact and cavitation of ultrasound propagating in the liquid increased the porosity and surface area of stalk (Wu et al., 2017). Dong et al. (2018) proposed the dual-frequency ultrasound combined with alkali pretreatment, which used the cavitation and mechanical effects of ultrasound. High-frequency ultrasound disrupted the cell wall of corn stalk, and low-frequency ultrasound promoted the breakage of the connection between lignin, hemicelluloses and cellulose. The method improved utilization of corn stalk, enhanced the effect of pretreatment, and increased gas production. In this paper, dual-frequency ultrasound combined with alkali (a physical and chemical combination process) was used to pretreat corn stalk.

The main methods for obtaining the optimal pretreatment parameters at present are orthogonal experimental design (OED), response surface methodology (RSM), and uniform design (UD). The OED is a multi-factor experiment design method based on the orthogonal array, and the method selects representative points from full factorial experiment. The representative experiments distribute uniformly in the experimental range and thus can represent the overall points, and it is

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highly efficient for the arrangement of multi-factor experiment with optimal combination levels (Zhu et al., 2013). However, the optimal levels combination obtained from data analysis is within the experimental range, and it is difficult to achieve the global optimum. The RSM uses a polynomial function to approximate the implicit limit state function through a series of deterministic experiments (Mohammadi et al., 2016). The linear response surface has high approximation accuracy if the limit state function is not highly nonlinear. The UD selects the experimental points uniformly in the experimental domain, and a regression model suitable for the experimental data is established based on the experimental results to find the optimal parameter combination (Fang et al., 2000). The RSM and UD methods based on mathematical models between factors and targets through experimental results essentially belong to the multiple regression method, and the regression equation is only an assumption, which affects the diversity of factors and the unpredictability of some factors. The accuracy of both RSM and UD methods is not high if the experimental data are not enough, which limits their applications range.

In recent years, artificial intelligence methods, such as artificial neural networks (ANN), have been successfully applied to establish prediction models between experimental factors and targets to obtain the optimal combination of process parameters (Singh et al., 2017; Zekovic et al., 2017; Boukelia et al., 2016). The main advantage of ANN compared with RSM is that ANN can approximate any nonlinear mapping, including quadratic functions, while RSM is only suitable for fitting quadratic functions (Desai et al., 2008; Sabour and Amiri, 2017). But the ANN training algorithm converges slowly and easily falls into local optimum, and it is not suitable for modeling with small sample data. Support Vector Machine (SVM) based on statistical learning theory was proposed by Vapnik (1995). The type of machine is typically formulated using quadratic optimization under the umbrella of convex optimization (Pablo et al., 2013), and it only uses the support vectors rather than any other samples to fit a function. With the unique property of SVM, the solution is always global and easy to compute for very small data problems. LS-SVM is an improved model of SVM. The loss function of LS-SVM is represented by the 2-norm of the error, and the equality constraint is used to replace the inequality constraint condition in SVM, so the convergence speed is improved. Although LS-SVM is being using to model regression problems related prediction, there is no report dealing with LS-SVM applied to optimization process parameters for anaerobic fermentation of corn stalk.

The purpose of this paper is to propose a method that combined OED with LS-SVM to set up a prediction model between CBP during anaerobic fermentation of corn stalk and pretreatment process parameters. 2D and 3D contours of the prediction model were used to analyze the effect of process parameters on the CBP, and the optimal combination of pretreatment process parameters will be obtained in order to maximize the CBP.

2. Material and methods

2.1. Materials and devices

Corn stalks used in the experiments were collected from Shunyi District of Beijing, and the anaerobic seed sludge came from a sewage treatment plant in Beijing. The content of the total solids (TS) of the corn stalks and the inoculum sludge are $(90.3 \pm 0.03)\%$and$(8.5 \pm 0.05)\%$ respectively; and their content of volatile solid (VS) are $(87.7.\ 3 \pm 0.13)\%$ and$(4.6 \pm 0.06)\%$ respectively.

The ultrasonic generator is composed of an external groove probe device and an ultrasonic immersion probe. The external groove device is made up of 8 ultrasonic transducers that are adhered around the body. The ultrasonic frequency of the transducer is 20 kHz, and the maximum electric power is 900 W. The frequency and maximum electric power of ultrasonic immersion probe of 1.9 cm in diameter are 57 kHz and 800 W respectively. The transmitter end of the horn is directly immersed in the sample to be treated when used. Electric power of the ultrasonic generator can be adjusted by duration time of the ultrasound, and the temperature of the sample to be treated is controlled by water bath.

A device of anaerobic digester consists of a 1 L glass bottle (working volume 0.8 L), a 1 L jar and a 1 L beaker, and they are connected by anti-corrosive rubber tube. The glass bottle is used as an anaerobic digestion reactor, and the jar is used to measure the daily displacement, that is, the daily gas production; the beaker is used to collect the daily drainage. All reactors are placed in a constant temperature water tank.

2.2. Methods of experiment and analysis

The corn stalks, which had been chopped and screened, were pretreated in different schemes. Then the pretreated stalks were added to the reactors. Anaerobic seed sludge was added according to the mixed liquor suspended solid (MLSS) of 15 (g/L TS); and the ratio of carbon to nitrogen (C/N) in the reactor was adjusted by NH4Cl to 20:1. The mixtures in the reactors were charged with water to 0.8 L, and pH values of the mixture were adjusted from 7.0 to 8.0 by NaOH; Finally, the connected reactors were put into a constant temperature ((35 ± 1)°C) water tank for anaerobic fermentation.

The daily biogas production is collected with drainage method (Zhou et al., 2012), and the biogas composition, including methane, carbon dioxide, hydrogen and nitrogen are determined by a meteorological chromatography (SP-2100, Beijing HuiJie Analysis Technology Co., Ltd.). The specific parameters are as follows: chromatographic column: 2 m × 3 mm stainless steel column, filler for the TDX-01; the carrier gas is H_2, the flow rate is 30 mL/min; detector is a thermal conductivity detector; detection temperature, oven temperature, sample temperatures are 150 °C, 120 °C, 150 °C, respectively; excitation current is 150 mA; and the gas retention time are N_2:0.727 min, CH_4:1.750 min, CO_2:3.249 min. TS and VS are measured according to standard methods for the Examination of Water and Wastewater (Standard Methods for the Examination of Water and Wastewater, 1992).

3. Experimental design and prediction model

In this paper, the OED method was used to design and arrange experiments. And the representative points of OED were selected from full-factorial pretreatment experiments of corn stalk. In the experiments, the daily gas productions were collected off-line and recorded, and then the CBPs were obtained to prepare data for modeling. The LS-SVM was trained using the small-sample data collected from the experiments to obtain a prediction model of CBP for anaerobic fermentation of corn stalk.

3.1. Orthogonal experimental design and results

In this study, weight of corn stalk (Zheng et al., 2009), ultrasonic duration time, alkali pretreatment (2% NaOH) time, and single/dual-frequency ultrasound were selected as the experimental factors of OED, and each factor had 3 levels. The three levels of different factors were chosen for the experiments (Table 1). The orthogonal analysis of $L_9(3^4)$ was chosen because it could be used to study 4 factors. Those levels were distributed in the orthogonal analysis of $L_9(3^4)$, and the CBP for each anaerobic digester was recorded (Table 2).

K_i and k_i represent the impact of level i of each factor to the CBP. The higher the K_i and k_i are, the higher CBP is. k_{max} is the maximum among three k_i values of each factor and k_{min} is the minimum. R represents the range, and the factor that has higher R suggests a stronger impact on the CBP of anaerobic fermentation (Table 2). K_i, k_i and R were calculated respectively as follows:

$$K_i = \sum CBP_i, \quad i = ,1, 2, 3 \tag{1}$$