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Evaluation of two statistical methods for optimizing the feeding composition in anaerobic co-digestion: Mixture design and central composite design

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HIGHLIGHTS

- ▶ Statistical methods were to optimize feeding composition in anaerobic co-digestion.
- ▶ Simplex-centroid mixture design (SCMD) and central composite design (CCD) were shown.
- ▶ SCMD and CCD developed optimum proportions of substrates for high methane potential.

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ABSTRACT

To investigate the feasibility of statistical methods in optimizing the feeding composition in anaerobic co-digestion, a simplex-centroid mixture design (SCMD) and central composite design (CCD) were evaluated with methane potential as the response variable. Dairy manure, chicken manure, swine manure and rice straw (RS) were selected as raw materials and two kinds of manures and RS were mixed in each blend. Each component served as an independent variable in the SCMD and CCD and involved two factors, the manure and C/N ratios. Co-digestion of three-component substrates resulted in higher methane potentials than single and two-component substrates. In response surface plots, SCMD showed the interactions among each component in the co-substrates and CCD presented the interaction between the ratio of manures and the C/N ratio. SCMD and CCD are both suitable methods for optimizing the feeding composition during anaerobic co-digestion.

1. Introduction

Anaerobic digestion is a widely used technology for organic solid waste treatment and energy recovery with several full biogas plants under operation. In the past decade, this technology has received great attention because of energy shortages and environmental problems. However, there are often insufficient amounts of waste from particular resources for large-scale digesters. Single substrates have drawbacks, including non-optimum carbon/nitrogen (C/N) ratios, low pH of the substrate itself, poor buffering capacity, and high concentrations of ammonia (Abouelenien et al., 2010; Zeshan et al., 2012; Procházka et al., 2012). Consequently, co-digestion of mixtures of substrates for biogas production has attracted interest.

Co-digestion is the anaerobic treatment of a mixture of at least two different waste types with the aim of improving the efficiency of the anaerobic digestion process (Álvarez et al., 2010). It is a particular form of anaerobic digestion and is a new and attractive approach for improving the efficiency of biotransformation. Previous studies have shown that co-digestion of mixtures of substrates may result in better digestion performance. This occurs through use of feed substrates with balanced nutrient composition, which stimulate the synergistic effects of microorganisms (Agdag and Sponza, 2007), an associated increase in buffering capacity (Murto et al., 2004), and a reduced effect of toxic compounds on the digestion process (Ahring et al., 1992).

Sources of wastes suitable for anaerobic digestion are extensive, including the organic fraction of municipal solid waste (OFMSW), agricultural wastes and residuals, industrial waste, energy crops and sewage sludge. Co-digestion of these has been widely reported (Mata-Alvarez et al., 2011). Theoretically, random mixtures of these wastes could be used as co-substrates for digestion. However, it is more desirable that they actually be selected and mixed according

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to some criteria. Substrate composition is a major factor in determining the methane yield and methane production rates from the digestion of biomass. The main benefit of co-digestion lies in balancing several parameters in the co-substrate mixture: macro and micronutrients, C/N ratio, pH, inhibitors/toxic compounds, biodegradable organic matter, and dry matter (Hartmann et al., 2003). Thus, the proportion of different substrates in the mixture is a crucial factor influencing the efficiency of anaerobic co-digestion.

In most research, the proportions of the mixture components are selected randomly. There is very little information on optimizing the waste proportions to maximize the digestion efficiency. Rao and Baral (2011) used the mixture design method to investigate the synergetic effects of mixed substrates in batch experiments and to establish the optimum mixture combination. They showed that statistical techniques are available for optimizing feeding composition. Álvarez et al. (2010) developed a linear programming optimization method based on determining restrictions (COD/N, NH^+_4 -N and lipid) on several characteristics of the mixture to determine the most adequate ratios of different co-substrates that provide an optimized biodegradation potential or biokinetic methane potential.

The purpose of this study was to investigate the feasibility of two methods, mixture design and central composite design, for optimizing the feeding composition of anaerobic co-digestion. Mixture design is used to study relationships among proportions of different variables and responses, and components can be set directly as variables. For the central composite design, the C/N ratio was used as one factor that was set within a proper range for co-digestion. Another factor was the ratio of manures in a three-component blend. For this purpose, dairy manure (DM), chicken manure (CM), swine manure (SM) and rice straw (RS) were selected as raw materials and two kinds of manures plus RS were mixed in each blend.

2. Methods

2.1. Substrates and inoculum

DM, CM and SM were collected from a livestock farm located in Yangling, China. RS was obtained from a local villager and was air dried and cut into 2–3 cm pieces before being added to the reactor. The anaerobic sludge used as the inoculum was collected from an anaerobic digester in a local village. The substrates and inoculum were individually homogenized and subsequently stored at 4 °C for further use. The chemical characterization of each substrate and the sludge tested in this study are presented in Table 1. All samples were collected in triplicate, and averages of the three measurements are presented.

2.2. Experimental set-up

Anaerobic batch digestion tests were carried out in triplicate at 35 °C for 30 days according to the method described by Wang et al. (2012a). The initial volatile solid (VS) ratio of substrate to inoculum was maintained at 1:2 for all the experimental setups. Each reactor had a 1 L capacity and contained 600 mL of total liquid, including 200 mL of inoculum and mixed substrates of 15 gVS/L. All reactors were tightly closed with rubber septa and screw caps. After adding the feedstock to the reactors, the reactors were flushed with nitrogen gas for about 3 min and sealed immediately with butyl rubber stoppers. To aid the mixing of the reactor contents, all reactors were shaken manually for about 1 min once a day prior to the measurement of biogas volumes.

Table 1
Chemical characterization of substrates used in the digestion experiments.

Material	pH	TS (%)	VS[a] (%)	Organic carbon[a] (g/kgVS)	TKN[a] (g/kgVS)	C/N
DM	7.23	13.9	77.4	62.8	2.67	23.5
CM	6.88	24.8	64.3	55.4	6.14	9.02
SM	7.15	22.0	78.7	78.3	6.03	13.0
RS	ND[b]	86.1	90.6	328	6.34	51.7
Inoculum	7.88	4.86	68.7	ND[b]	ND[b]	ND[b]

[a] Dry weight basis.
[b] Not determined.

2.3. Experimental design and statistical analysis

2.3.1. Simplex-centroid mixture design (SCMD)

The SCMD method was used to determine the optimum mixture proportion of selected substrates in the anaerobic co-digestion of methane. The mixture contained three components, and the mixture space was a triangle whose vertices corresponded to pure blends (mixtures that are 100% of a single component) (Montgomery, 2008). Three mixture sets were investigated in this experiment: set A (DM, CM and RS), set B (DM, SM and RS), and set C (CM, SM and RS). The proportions of all substrates in each mixture were in VS basis. Each mixture gave an initial loading of 15 gVS/L. Table 2 presents the experimental sets produced by Design-Expert software (version 7.5, Stat-Ease, Inc. Minneapolis, Minnesota) with 13 runs for each set, and the response variable being methane potential based on the methane yield and VS added.

The SCMD method can not only establish the surface model of continuous variables, estimating each component in the mixture and their interactions, but can also optimize the proportions of all components according to the target (Muteki and MacGregor, 2007; Martinello et al., 2006). The standard forms of the mixture models that are widely used are linear, quardratic, special cubic, full cubic and special quartic models (Rao and Baral, 2011). The results and regression coefficients were completely analyzed using the analysis of variance (ANOVA) by Design-Expert software. Response optimization of mixture proportions was used to identify the combination of input variable settings that jointly optimize the responses (Rao and Baral, 2011).

2.3.2. Central composite design (CCD)

CCD was applied to design the experimental conditions using Design-Expert software involving two factors, the ratio of different manures (M_1/M_2) and the C/N ratio. This experiment included three sets: set D (DM, CM and RS), set E (DM, SM and RS), and set F (CM, SM and RS). Table 3 showed the levels of the variable factors in the experiment and the experimental design with the parameters in coded and actual terms. The proportions of all substrates in each blend were in VS basis. Each blend had an initial loading of 15 gVS/L, so the appropriate amount of RS was added to adjust the C/N ratio to specific levels based on M_1/M_2. The selected responses for analysis were methane potential based on the methane yield and VS added.

Response surface methodology (RSM) was used to optimize the studied parameters. With RSM, the interaction of possible influencing parameters on methanogenesis can be evaluated with a limited number of planned experiments. Functional relationships between responses (Y) and the set of factors (X_1 and X_2) were described by estimating coefficients of the following second-order polynomial model based on experimental data.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2$$

Where Y represents the predicted response of methane potential, X_1 is the ratio of M_1/M_2; X_2 is the ratio of C/N; β_0 is a constant; β_1 and β_2 are linear coefficients; β_{12} is interaction coefficients and β_{11} and β_{22} are quadratic coefficients.