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Optimization of co-digestion of various industrial sludges for biogas production and sludge treatment: Methane production potential experiments and modeling

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ABSTRACT

Optimal biogas production and sludge treatment were studied by co-digestion experiments and modeling using five different wastewater sludges generated from paper, chemical, petrochemical, automobile, and food processing industries situated in Ulsan Industrial Complex, Ulsan, South Korea. The biomethane production potential test was conducted in simplex-centroid mixture design, fitted to regression equation, and some optimal co-digestion scenarios were given by combined desirability function based multi-objective optimization technique for both methane yield and the quantity of sludge digested. The co-digestion model incorporating main and interaction effects among sludges were utilized to predict the maximum possible methane yield. The optimization routine for methane production with different industrial sludges in batches were repeated with the left-over sludge of earlier cycle, till all sludges have been completely treated. Among the possible scenarios, a maximum methane yield of 1161.53 m^3 is anticipated in three batches followed by 1130.33 m^3 and 1045.65 m^3 in five and two batches, respectively. This study shows a scientific approach to find a practical solution to utilize diverse industrial sludges in both treatment and biogas production perspectives.

1. Introduction

In order to accomplish the recently declared objective 'Low Carbon, Green Growth', the Ministry of Environment (MOE), South Korea has started the 'Waste Resources and Biomass Energy Utilization Initiatives' which aim to convert 26% of organic wastes to energy through the biogasification process by 2013 (Marchaim, 1992; Lema and Omil, 2001; McCarty, 2001; MOE, Korea, 2009). The reduction of industrial and municipal sludges through anaerobic digestion and followed by an aerobic treatment such as composting could be considered as an environmental friendly methodology (Abdullah and Chin, 2010).

Waste sludge generated from various industries differ significantly in both their qualities and quantities and depends on the industrial processes and products. It is not feasible and economic to treat these industrial sludges in separate 'on-site anaerobic digestor' at each plant rather to install a centralized treatment facility for all combined sludge together (Dagnall, 1995). It is noteworthy that some of sludges are poorly biodegradable due to their low solubility or suboptimal C/N ratio, however, degrade satisfactorily in certain combinations (Azbar et al., 2008). The anaerobic co-digestion of diverse organic wastes together can improve nutrient balance, dilute potentially toxic compounds such as sulphur-containing substances, and subsequently increase the processing capacity and biogas yield (Sosnowski et al., 2003). Some antagonistic and synergistic relationships exist among diverse industrial sludges that may interfere with their digestion as well as methane yield in co-digestion process. It is necessary to investigate these relationships among the pair of sludges to design a cost effective co-digestion strategy for complete treatment of all sludges with maximum possible biomethane production. It is more realistic to digest these diverse sludge in selective batches of co-digestion process on the basis of synergistic correlations among sludges to get both economic and environmental benefits through the complete treatment of all industrial sludges.

To optimize the anaerobic co-digestion process, the mixture design technique is often used to identify the best subset of interactions among components (Misi and Forster, 2001; Cornell, 2002; Sánchez-Arias et al., 2008; Abdullah and Chin, 2010; Wang et al., 2013). The improvement in specific methane yield (SMY_{wt}) may not only be sufficient to justify the adoption of a co-digestion process from an industrial perspective, rather it must also include the quantity (in ton) of sludge (QS_{wt}), i.e. being considered for

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Table 1
Characterization of organic sludge from five representative industries in Ulsan Industrial Complex.

Industrial category/ product	Sludge generated ($t\,d^{-1}$)	pH	TS (gL^{-1})	VS (gL^{-1})	VS in wet weight (% w/w)	COD (gL^{-1})	Alkalinity (mg L^{-1} $CaCO_3$)	Elemental composition-based formula
Paper bleaching (P) *chemical pulp*	325.04	7.95	43.87	19.05	1.809	34	13,100	$C_{12.6}H_{21.9}O_{14.7}N$
Chemical (C) *NaOH, urea, melamine*	79.38	6.95	37.41	10.05	2.906	5.2	3720	$C_{8.9}H_{113.7}O_{33.7}N$
Petrochemical (PC) *Polyester chip*	26.36	8.37	14.40	9.00	1.083	11.66	1040	$C_{15.3}H_{7.2}O_{7.0}N$
Automobile (M) *Car*	30.34	7.82	8.18	4.46	0.871	14.73	1143	$C_{9.3}H_{19.2}O_{5.5}N$
Food processing (F) *Sugar*	6.71	7.89	13.54	6.52	0.761	13.5	431	$C_{15.5}H_{20.3}O_{8.7}N$

maximum possible treatment in an optimum number of co-digestion batches. Therefore, a multi-objective optimization strategy is formulated wherein two or more responses are simultaneously evaluated to generate a global optimum solution (Videla et al., 1990). In multi-objective optimization techniques, several tools such as genetic algorithm, neural network, response surface methodology, and desirability function have been used (Sáiz-Abajo et al., 2005). The desirability function seems to be an effective tools that have the ability to transform the several responses separately and comprises all of them in an overall combined desirability function to give the global optimal solutions.

The scope of this work was to evaluate and optimize the complete anaerobic digestion of sludges of five representative industries situated in Ulsan Industrial Complex, South Korea. Biomethane production potential test was conducted in simplex-centroid mixture design and the specific methane yield (SMY_{wt}) was mathematically represented by the quadratic polynomial equation. Simultaneous optimization of two factors such as SMY_{wt} and QS_{wt} were carried out using the combined desirability function with differential weightage to provide the optimal solutions for maximum possible digestion of these industrial sludges in optimum numbers of co-digestion batches.

2. Materials and methods

2.1. Industrial organic sludge and inoculum

The thickened organic sludges were collected from the wastewater treatment facilities of paper (P), chemical (C), petrochemical (PC), automobile (M), and food processing (F) industries situated in Ulsan Industrial Complex (UIC), Ulsan, South Korea. The various characteristics of the selected industrial sludge are given in Table 1. Anaerobic seed culture (inoculum) was collected from the mesophilic anaerobic digesters at the Yongyeon municipal wastewater treatment plant in Ulsan, South Korea.

2.2. Simplex-centroid mixture design and experimental setup

In this study, the biomethane potential experiments were conducted under five-component mixture design using sludges of five representative industries. An un-constrained simplex centroid design with (2^5)-1 distinct base design points augmented with five axial data points was consisted of total 36 experimental runs (Table 2). The mixture design module in a statistical software Minitab (version 16.0, Minitab Inc., State College, PA) was used to navigate the experimental data by quadratic polynomial equation.

The batch biochemical potential experiments were carried out in two replications at a time in 150 ml serum bottles with a working volume of 100 ml and capped with natural rubber sleeve stoppers. Anaerobic seed sludge mixed thoroughly and filtered through 1 mm sieve was added to each serum bottle at a concentration of 2 g/l VS equivalent. Subsequently, the contents were diluted with 40 ml of mineral salt medium containing vital micro- and macro-nutrients (Owen et al., 1979). The industrial sludges were dispensed into the serum bottles based on the experimental design to a final concentration of 1.0 g/l VS equivalent. Alkalinity was adjusted to 5000 mg/l of $CaCO_3$ equivalent (pH $\sim$ 7.8) to remain within the limits of normal anaerobic treatment (Rittmann and McCarty, 2001). The serum bottles were dosed with 3.1 ml/l of Na_2S (2% w/v) and subsequently purged with N_2 to maintain the anaerobic condition. The bottles were immediately crimp-capped and incubated in a thermostatic shaker at 35 °C. Biogas production was measured at regular intervals.

2.3. Analytical methods

The moisture content (MC), total solid (TS), fixed solid (FS), volatile solid (VS), and alkalinity of samples was analyzed in accordance with standard methods (APHA, 1998). The values reported are the averages of duplicate samples with relative errors <5%. Biogas was collected from the serum bottles every 1–2 days in a graduated gas-tight glass syringe at atmospheric pressure and the volume was measured. The volume of biogas produced was corrected to the standard temperature and pressure (STP) conditions. Methane content in biogas was analyzed using a gas chromatograph (GC) (DS 6200, Donam Instruments, Daejon, South Korea) fitted with a porapaq Q column (1.8 m (6 ft), 80/100 mesh) and a thermal conductivity detector (TCD). The carrier gas used was helium, while the temperatures of the oven, injector port and detector were maintained at 35, 120 and 120 °C, respectively, as described previously (Behera et al., 2010).

2.4. Modeling of co-digestion of industrial sludge using a quadratic polynomial equation

Specific methane yield based on sludge VS content (SMY_{vs}) is a simple function of mixture composition, if the other parameters are kept constant. In the sludge mixture, the component VS proportions (x_i) out of total substrate content are non-negative ($0 \leqslant x_i \leqslant 1.0$) that sum upto unity (Cornell, 2002). When synergism and/or antagonism are expected from blending/mixing among the components, the response surface can be represented by Eq. (1), the nth-order polynomial function.

$$SMY_{vs} = \sum_{i=1}^{n}\beta_i x_i + \sum_{i=1}^{n}\sum_{i<j}^{n}\beta_{ij}x_i x_j + \sum_{k=1}^{n}\sum_{j<k}^{n}\sum_{i<j}^{n}\beta_{ijk}x_i x_j x_k + \ldots + \beta_{12\ldots n}x_i x_j \ldots x_n \quad (1)$$

where β_i and β_{ij} are the coefficients of linear and interactive effects of sludge "i" and "j", respectively, with a VS fraction of x_i.

The above mixture design model is based on sludge VS, which is rather the biodegradable fraction. However, total sludge generated in industry is reported in terms of wet weight. Thus amount of