Optimising biogas fermentation using the Taguchi methodology

Sreenivas Rao Ravella, Phil Hobbs, Jon Williams and Andy Retter
Institute for Grassland and Environmental Research, North Wyke, Okehampton,
Devon. England.EX20 2SB
Contact sreenivas.rao-ravella@bbsrc.ac.uk

Abstract

This study investigated how to optimize biogas production, in this case for five parameters which were hydrolysis temperature, fermentation temperature, substrate concentration, mixing and inoculum volume. Biogas production was optimized by a specific factorial design methodology known as the Taguchi orthogonal array (OA) experimental design (DOE) methodology. This approach facilitates the study of interaction of a large number of variables spanned by factors and their settings with a small number of experiments leading to considerable saving in time and cost for process optimization. The proposed Taguchi DOE methodology consists of four sequential phases viz., planning, conducting analysis and validation to achieve the overall process optimization. Five factors viz., hydrolysis temperature, fermentation temperature, substrate concentration, mixing, inoculum size, at two levels with an OA layout of L_8 were selected for the proposed experimental design. Biogas yield obtained from the 8 sets of fermentation experiments performed with the selected factors and levels were further processed to obtain a higher degree of accuracy with the larger dataset.

This methodology facilitated rapid analysis of the experimental data to establish the optimum conditions for biogas production and understand the contribution of individual factors and to evaluate the response under optimal conditions. The optimum conditions required no pre hydrolysis, with 6% w/v pig feed, at 35^0C with high inoculum concentration and with continuous stirring. The Taguchi approach has potential usage in other bioprocess optimizations.

Keywords: biogas, Taguchi methodology, factorial design, fermentation

Introduction

Microbial production of biogas has become one of the most attractive technologies for energy production. During methanogenesis numerous acid-forming bacteria are associated with methanogens. The products of fermentation vary considerably, depending on the bacteria involved in the fermentation. Therefore, changes in environmental conditions that result in changes in dominant bacterial species, also result in changes in the concentrations of acids, alcohols etc. that are produced during fermentation. Such changes determine the substrates ultimately available for the methanogens, their activity and, consequently, overall performance of methanogenesis. The process is very dynamic and for the optimization of this process it is very important to know the individual factors that effect the fermentation.

Traditional method of process optimization involves the study of one-variable-at-a-time which requires a number of combinations of experiments that are time, cost and labour-intensive. The Taguchi method of design of experiments is a simple statistical tool involving a system of tabulated designs (arrays) that allows maximum number of main effects to be estimated in an unbiased (orthogonal) fashion with minimum number of experimental runs. (Sreenivas et al 2008).

In the Taguchi method, variables or factors are arranged in an orthogonal array (OA). The orthogonal array properties are such that between each pair of columns each combination of levels (or variables) appears an equal number of times. Due to an orthogonal layout,

the effects of the other factors can be balanced and give a relative value representing the effects of a level compared with the other levels of a given factor. In orthogonal array experiments, the number of test runs is minimized while keeping the pair wise balancing property. Taguchi methods utilize two-, three-, and mixed-level fractional factorial designs. Taguchi designs are similar to the familiar fractional factorial designs. Nevertheless, Taguchi has introduced several noteworthy new ways of conceptualizing an experiment that are very effective for product development and industrial engineering.

Materials and Methods

Eight bench-scale bioreactors were constructed from 5 L glass culture vessels. A 48 cm · 6 mm diameter stainless steel tube is bent in a gentle J-shape with a bend of 30^0 from the vertical over the lower 15 cm of its length and any sharp edges are removed from the lower end by grinding. The bent length of the stir rod is lightly coated with silicone grease and inserted into a 38 cm length of 12.5 mm ID · 17 mm OD flexible plastic tubing, which is sealed at the end with a 14/18 neoprene bung. The open end of the tubing is inserted through a 19/26 hole in the center of the reactor lid such that it flush with the top of the lid's central port, with the steel rod extending 11 cm above the tubing. The protruding rod is coupled to a 60-rpm motor (W.W. Grainger, Inc., Lake Forest, IL). Gas is collected and measured by water displacement in a calibrated, inverted cans. (Wilkie et al 2004)

In the present optimization study 5 columns are assigned with different factors as indicated in Table 1. All the factors have been assigned only with two levels. Hence it has nine level 1 and four level 1 and four level two conditions. (2^5). Qualitek -4 Software was used for designing experiments and for the analysis. Preliminary experiments were conducted to choose the levels. Hydrolysis was monitored by sugar estimations and VFA analysis. VFAs were analyzed with Thermo Electron High Performance Liquid Chromatography HPLC using a Bio Rod Column (125-0115). H_2SO_4 (1mM) was used as a mobile phase with a flow rate of 0.5mL/min. The detection was carried out at ambient temperatures with a diode array UV detector at 220nm.

Table 1: Factors and their levels assigned to different columns

S.No.	Factor	Level 1	Level 2
1	Pre hydrolysis	without	with
2	Temperature OC	35	40
3	Substrate Concentration w/v	4%	6%
4	Inoculum (%, v/v)	Low (15)	High (30)
5	stirring	Continuous	on (8 h a day) and off

Table 2: L_8 (2^5) Orthogonal Array

Experiment No.	Column							
	1	2	3	4	5	6	7	Biogas production l/day
1	1	1	0	1	0	1	1	0.400
2	1	1	0	2	0	2	2	3.100
3	1	2	0	1	0	2	2	2.500
4	1	2	0	2	0	1	1	0.250
5	2	1	0	1	0	1	2	1.300
6	2	1	0	2	0	2	1	0.400
7	2	2	0	1	0	2	1	0.250
8	2	2	0	2	0	1	2	0.500

Table 2 shows the layout of the L_8 (2^5) orthogonal array used in the present study. All the combination experiments using the assigned parameter values were conducted using pig feed as a feedstock. Biogas productions from the reactors were shown in Table 2 and main effects in Table 3.

The percentage contributions of each factor are shown in an ANOVA table (Table 4). The last column of the ANOVA indicates the influence of each factor. Stirring continuously of the reactors was the most significant factor for biogas production, pre hydrolysis of pig feed and inoculum showed moderate effect on biogas production. The remaining factors incubation temperature and substrate concentration showed negligible influences on the biogas production at their individual levels.

Table: 3 Main effects

S.No.	Factor	Level 1	Level 2	L2 - L1
1	Pre hydrolysis	1.637	0.612	-1.026
2	Temperature OC	1.375	0.875	-0.500
3	Substrate Concentration	1.112	1.137	0.024
4	Inoculum (%, v/v)	0.612	1.637	1.025
5	stirring	0.325	1.925	1.599

Table: 4 Analysis of Variance (ANOVA)

S.No	Factors	DOF	Sums of squares	Variance	F-Ratio	Pure sum	percent
1	Pre hydrolysis	1	2101250	2101250	42025000000	2101249	21.389
2	Temperature OC	1	500000	500000	10000000000	499999	5.089
3	Substrate	1	1250	1250	25000000	1249	0.012
	Concentration						
4	Inoculum (%, v/v)	1	2101250	2101250	42025000000	2101249	21.389
5	stirring	1	5120000	5120000	102400000000	5119999	52.118
Other/Error		2	0	0			0.003
Total:		7	9823750				100.00%

Table 5: Estimated interaction of severity index for different parameters

S.No.	Factors	Columns@	SI (%)	Col	Levels
1	Temperature x substrate conc	2 x 4	67.21	6	[1,2]
2	Pre hydrolysis x inoculum	1 x 6	60.95	7	[1,2]
3	Pre hydrolysis x stirring	1 x 7	39.04	6	[1,2]
4	Inoculum x stirring	6 x 7	39.04	1	[2,2]
5	Substrate conc x inoculum	4 x 6	32.78	2	[2,2]
6	Pre hydrolysis x substrate conc	1 x 4	25.45	5	[1,2]
7	Temperature x stirring	2 x 7	16.66	5	[1,2]
8	Pre hydrolysis x Temperature	1 x 2	1.63	3	[1,1]
9	Temperature x inoculum	2 x 6	1.63	4	[1,2]
10	Substrate conc x stirring	4 x 7	1.53	3	[2,2]

@ Columns - Represent the column locations to which the interacting factors are assigned.

Table 5 indicates the interaction between two selected factors. The interaction was measured based on severity index value calculated by software program. This value between two selected factors varied (67.21 to 1.53%) with factor to factor (Table 5). It is clear that the interaction between two least biogas production influential factors (at their individual levels) showed the highest severity index (Table 5).

Optimum conditions and their performance in terms of contribution for achieving maximum biogas production are given in Table 6. It can be seen from the table that physical factor such as stirring played a significant role in product formation than the other selected parameters and their levels.

Table: 6 Optimum Conditions and Performance

S.No	Factors	Level Desc.	Level	contribution
1	Pre hydrolysis	without	1	0.512
2	Temperature OC	35	1	0.250
3	Substrate Concentration	6%	2	0.012
4	Inoculum (%, v/v)	High (30)	2	0.512
5	stirring	continuous	2	0.799

Total contribution from all factors… 2.084
Current grand average performance… 1.125
Expected result at optimum condition… 3.209

Conclusion

The Taguchi methodology predicted the optimum values for 5 factors for biogas production for a 5 litre vessel. The optimum condition for maximum biogas production in this experiment was without pre hydrolysis, with 6% w/v pig feed, at 35^0C with high inoculum concentration and with continuous stirring.

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