



OPERATING STUDY OF MICROWAVE TREATMENT SYSTEM USING DESIGN OF EXPERIMENT TECHNIQUE

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ABSTRACT

This paper presents the findings of an experimental investigation into the effects of irradiation power (PM), flow rate (FR), and treating number (NT) in anaerobic digestion of food industrial wastewater. A two-level factorial experiment has been used to accomplish the objective of the experimental study. The specific energy demand (SED) of microwave treatment was the response variable investigated. The experimental results indicate that the proposed mathematical models suggested could adequately describe the performance indicators within the limits of the factors that are being investigated.

Keywords: wastewater pre-treatment, biogas, microwave, anaerobic digestion

1. INTRODUCTION

Population growth, increasing living standards, but also environmental hazards with global climate change as the most significant are all contributing to an increasing water general demand and stress in many parts of the world. While access to fresh water for drinking water is getting more costly, uses of drinking water for agricultural and industrial use, which are in need of substantial water quantities, is a major problem. In addition as the general demand for water is growing, the amount of waste water produced and the pollution load are continually increasing. Despite its growing volume, sewage is also a reliable source of alternative water source if it can be recycled and resource can be recovered. In this sense sewage can be a cost-effective and sustainable energy source and it may also contain nutrients, organic substances and other useful by-products. From this point of view wastewater is no longer a problem that requires a solution but rather a solution to the challenges that society faces today. [8]

The chemical, thermal and hydraulic energy contained in wastewater can be recovered in the form of biogas, heating/cooling and electricity generation through on-site (in wastewater treatment plants) and off-site (in centralized plants) processes [2].

Biogas production from chemical energy contained in organic substances in wastewater through the anaerobic digestion of biosolids for subsequent electricity and heat generation is the most common application of on-site energy recovery. Biosolids in wastewater mainly comprised of microbial cells and extracellular polymeric substances (EPS) produced by the cells as part of their metabolic activity. The microbial cells and EPS form a matrix that is the substrate for the anaerobic digestion. With respect to their physical state, microbial cells represent a relatively unfavourable substrate for subsequent microbial degradation. A large part of the organic matter is compartmentalized within the microbial cell membranes. This microbial cell wall is a semi-rigid structure which provides sufficient intrinsic strength to protect the cell from osmotic lysis. It contains glycan strands cross-linked by peptide chains that give the walls resistance to biodegradation. Because of this, conventional biological digestion techniques require long hydraulic retention times. To improve digestion efficiency, the most logical approach is to disrupt the microbial cells in the sludge, to make the organic material inside the cell walls available [7]. The pre-treatment also has the goal of decreasing the particle size, allowing a greater surface area per unit volume available for degradation [6]. Disintegration may be performed by chemical, thermal, mechanical, or the combination of the previous techniques. The application of microwaves (MW) is one of the pre-treatment techniques. Additionally, it was reported that biogas production increased with the application of microwaves and that it was higher than the gas production obtained in tests subjected to the same temperature but with conventional heating. [1] Microwave pre-treatment is an energy-intensive and

therefore cost-intensive technique, so it is important to set the optimal operating parameters of the treatment. The optimization techniques of treating parameters through experimental methods and mathematical and statistical models have grown substantially over time to achieve a common goal of improving the process efficiency. To construct an approximation model that can capture interactions between n design variables, a full factorial approach may be necessary to investigate all possible combinations [3]. The experiments were conducted using two-level fractional factorial experiments while the statistical analysis was concluded in the form of analysis of variance (ANOVA). Other experimental design approaches commonly utilized for modelling responses are the Taguchi technique and response surface methodology (RSM).

2. MATERIALS AND METHODS

Wastewater was collected in a Hungarian medium-sized meat processing company; the sampling point was after the grease trap. Sewage originates from meat processing technology, mainly from the flushing and rinsing process of equipment (slicing and packaging machines, smoking chambers). To remove grit, particles and other large-sized solids a cloth filter was used. Table 1.

Pre-treatment was carried out in a continuous flow microwave treating system developed at University of Szeged. (Fig 1) It contains a water-cooled, variable-power magnetron (M) operating at 2450 MHz. High-voltage power supply (NF power supply) feeding the magnetron consists of two transformers, one of them produces cathode heating voltage and heating current, the other produces the anode voltage which can be controlled by the primary circuit of an external auto-transformer. With this device (PM scaled TTR) the power of the magnetron can be set as well. Electromagnetic energy of the magnetron spread over a resonant slot. Getting through this slot the energy gets in the toroidal resonator. [5]. During the operation of toroid resonator energy is given to the treated material. Material is transferred in the continues-flow microwave treating system by a peristaltic pump (PP) with variable flow.

Anaerobic digestion (AD) tests were carried out under controlled mesophilic temperature range ($35 \pm 0.2^\circ\text{C}$). in 12 mini continuously stirred laboratory scale reactors with 250 mL total volume, equipped with Oxitop C measuring system.

Pre-treatment conditions and accordingly energy demand were very different, therefore specific energy demand was determined. Due to the nature of the parameter, the lowest value is the best in terms of energetic. [10]

$$SED = \frac{E}{BP} \quad [JmL^{-1}] \quad (1)$$

where BP is biogas production [mL], E is the energy demand of pre-treatments was calculated from the power of the magnetron (P_M) [W] and the time of irradiation (t) [s].

$$E = P_M \cdot t \quad [J] \quad (2)$$

Table 1: Characteristics of wastewater

Parameter	Value
Total solid (TS) (mgL^{-1})	3210 \pm 296
Total organic carbon (TOC) (mgL^{-1})	834.1 \pm 35.3
Lipid(mgL^{-1})	115.1 \pm 21.7
Protein (mgL^{-1})	379.4 \pm 21.2

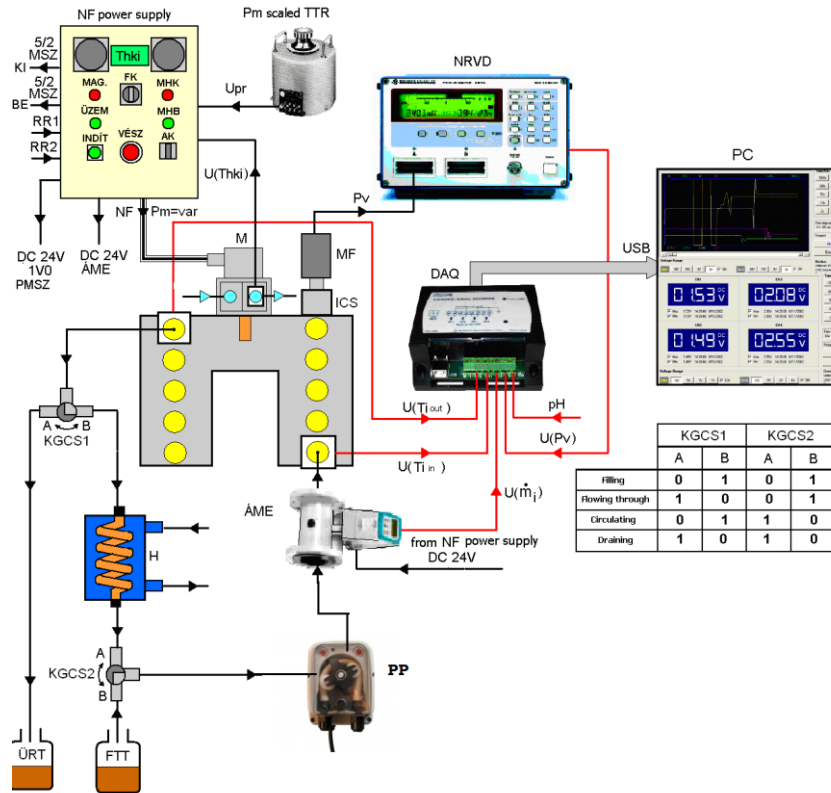


Figure 1. Microwave pre-treating system

A factorial experiment is an experimental strategy in which design variables are varied together, instead of one at a time. The lower and upper bounds of each of n design variables in the optimization problem needs to be defined. The allowable range is then discretized at different levels. If each of the variables is defined at only the lower and upper bounds (two levels), the experimental design is called 2^n full factorial. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). [4]

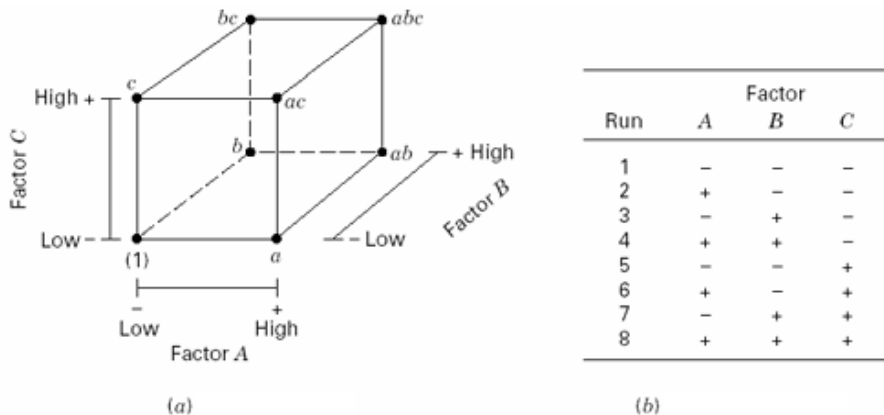


Figure 2: a) Geometric view of (2^3) factorial design b) design matrix of a 2^3 experiment [4]

Table 2: Factors and levels of operating parameters

Factors	Units	Low level (-1)	High level (+1)
(A) Power of the magnetron (PM)	W	300	700
(B) Flow rate (FR)	Lh ⁻¹	6	25
(C) Number of treatings (NT)	-	1	5

In some experiments, when the difference in response between the levels of one factor is not the same at all levels of the other factor, there is an interaction between the factors. The most important case of factorial design is the design for n factors, when the experiment is conducted at two levels for each factor, the high and low levels of a factor. In this case, a complete replicate of such a design requires (2^n) observations or 2^n factorial design. As shown in Fig 2, all treatment combinations can display geometrically as a cube. [11] The experiments were conducted to analyse the effect of power of the magnetron (PM), flow rate (FR), number of treating (NT) on the specific energy demand (SED). As a result (Table 2), each factor was set to the low (-1) and high (+1) levels. Two replications of each process conditions were conducted resulting in a total of 16 tests. Taking into consideration that over a certain value of irradiated microwave energy the degree of anaerobic decomposition was worsened, the PM and FR rate was set to achieve a range of 0.5-1.5Wg⁻¹. [9]

Regression algorithms are more robust, precise and show fewer round off and multicollinearity errors when variables are coded and centered, so PM, FR and NT values were codified according to expressions (3), (4) and (5), even though they could not be exactly centered

$$x_1 = \frac{PM - (PM_{high} + PM_{low}) / 2}{(PM_{high} - PM_{low}) / 2} \quad (3)$$

$$x_2 = \frac{FR - (FR_{high} + FR_{low}) / 2}{(FR_{high} - FR_{low}) / 2} \quad (4)$$

$$x_3 = \frac{NT - (NT_{high} + NT_{low}) / 2}{(NT_{high} - NT_{low}) / 2} \quad (5)$$

where x_1 is the coded factor that represents the power of the magnetron (PM), x_2 is the coded variable that represents the flow rate (FR) and x_3 is the coded variable that represents the number of treating (NT).

3. RESULTS AND DISCUSSION

The experimental plans were developed for establishing the quadric model of SED. These results were input into the Design Expert software. Therefore, the test for significance of the regression model, for significance on individual model coefficients and the test for lack-of-fit were performed to verify the goodness of fit of the obtained quadratic model. The analysis of variance (ANOVA) is usually applied to summarize the above tests performed. Without performing any transformation on the response, examination of the Fit Summary output revealed that the quadratic model is statistically significant for both responses and therefore it will be used for further analysis. The value of model "P > F" for the model is less than 0.05, which indicates that the term in the model have a significant effect on the response. The value of $P < 0.0001$ indicates that there is only a 0.01% chance that a "model F- value" this large could occur due to the noise. Values greater than 0.1000 indicate the model term is not significant.

Table 3: Analysis of variance (ANOVA) for SED

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	7.030E+006	6	1.172E+006	25.44	0.0002	significant
(A) Power of the magnetron (PM)	7.638E+005	1	7.638E+005	16.59	0.0047	
(B) Flow rate (FR)	2.056E+006	1	2.056E+006	44.65	0.0003	
(C) Number of treating (NT)	2.731E+006	1	2.731E+006	59.30	0.0001	
AB	2.556E+005	1	2.556E+005	5.55	0.0506	
AC	3.232E+005	1	3.232E+005	7.02	0.0330	
BC	9.005E+005	1	9.005E+005	19.55	0.0031	
Residual	3.224E+005	7	46053.82			
Pure Error	249.33	5	49.87			
Cor Total	7.353E+006	13				

The statistical significance of the fitted quadratic model for SED was evaluated by the F-test of the ANOVA, and shown in Table 3. When the values of the “Prob. > F” in the Tables 3 for the term of models are less than 0.05, indicates that the obtained models are considered to be statically significance, which is desirable, as it demonstrates that the terms in the model have a significant effect on the responses.

Table 4: Statistics regarding developed model for SED

Statistics	Value
Std. Dev.	214.60
Mean	784.86
Coefficient of variations	27.34
R-Squared	0.9562
Adj R-Squared	0.9186
Pred R-Squared	0.1173
Adeq Precision	19.388
PRESS	6.490E+006

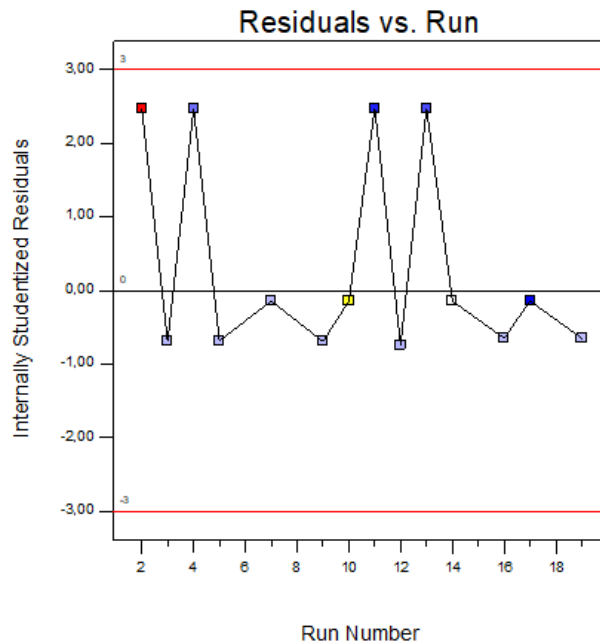


Figure 3: The comparison between measured and predicted value for SED

From Table 3 the Model F-value of 25,44 implies the model is significant. There is only a 0.01% chance that a “Model F-Value” this large could occur due to noise. Values of “Prob > F” less than 0.0500 indicate model terms are significant. In this case A, B, C, AC, BC are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

The “Pred R-Squared” of 0.1173 is in reasonable agreement with the “Adj R-Squared” of 0.9186. “Adeq Precision” measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 19.388 indicates an adequate signal. This model can be used to navigate the design space.

The regression model for SED in terms of actual factors is shown as follows:

$$SED = -833,26 + 1,5 \cdot PM + 46,64 \cdot FR + 314,57 \cdot NT - 0,094 \cdot PM \cdot FR + 0,5PM \cdot NT - 17,66 \cdot FR \cdot NT$$

The model obtained can be used to predict SED within the limits of the factors studied. The differences between measured and predicted responses are illustrated in Fig 3. The results of comparison were proved to predict values of SED close to those readings recorded experimentally with a 95% confident interval.

Fig 4-6 illustrate the contour plots of the interaction AB, BC and AC for SED respectively.

4. CONCLUSION

The purpose of this research is to quantify the effect of PM, FR and NT on SED. The factorial design was utilized to obtain the best operating condition which leads to the minimization of SED. ANOVA indicate that the (C) number of treating (NT) is the most significant factor followed by (B) flow rate (FR) and (A) power of magnetron (PM). Regarding the model validation, the regression model developed proves to be accuracy and has the capability to predict the value of response within the limits of factors investigated.

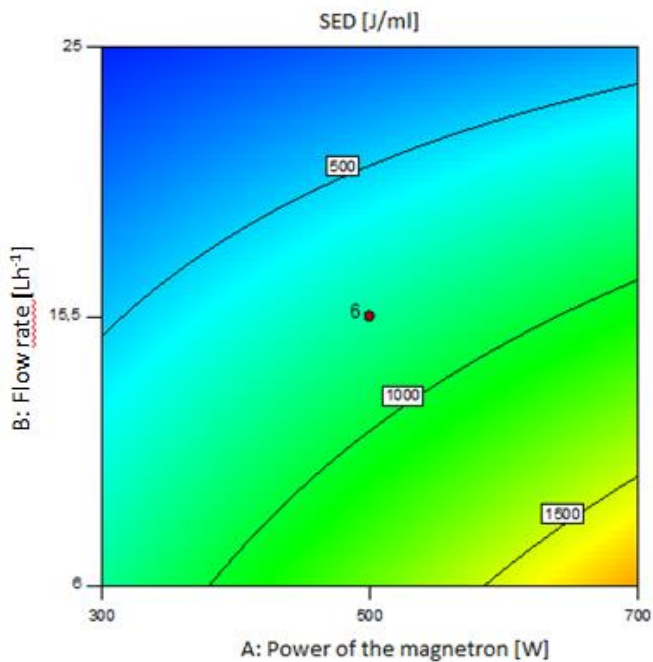


Figure 4: Contour plot of the interaction AB for SED

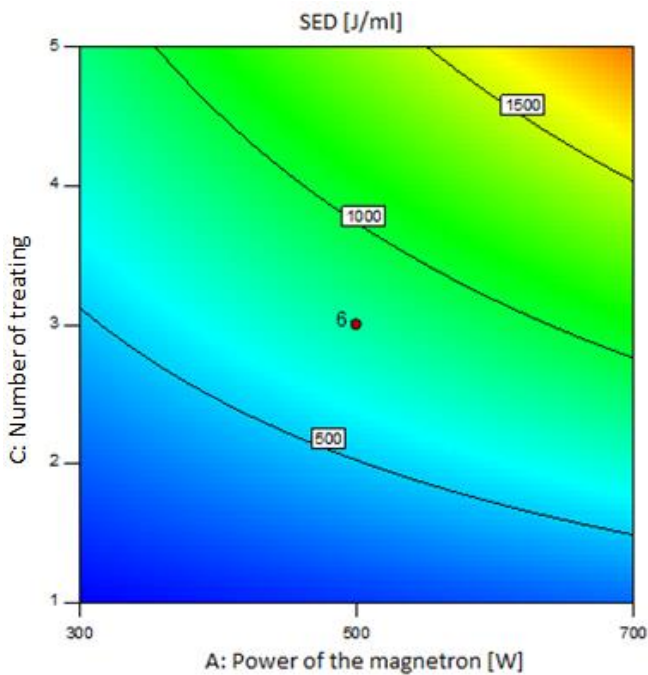


Figure 5: Contour plot of the interaction AC for SED

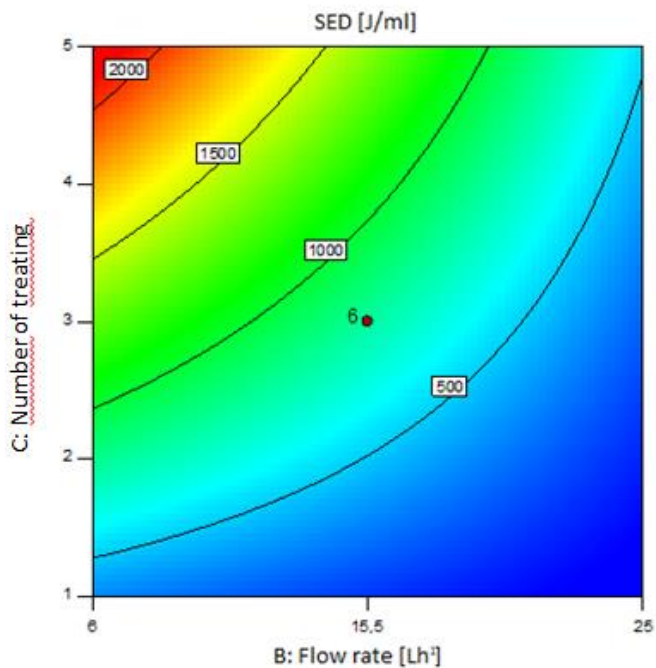


Figure 6: Contour plot of the interaction BC for SED

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