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Evaluating the influence of process parameters on soluble microbial products formation using response surface methodology coupled with grey relational analysis

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ABSTRACT

Soluble microbial products (SMPs) present a major part of residual chemical oxygen demand (COD) in the effluents from biological wastewater treatment systems, and the SMP formation is greatly influenced by a variety of process parameters. In this study, response surface methodology (RSM) coupled with grey relational analysis (GRA) method was used to evaluate the effects of substrate concentration, temperature, NH_4^+-N concentration and aeration rate on the SMP production in batch activated sludge reactors. Carbohydrates were found to be the major component of SMP, and the influential priorities of these factors were: temperature > substrate concentration > aeration rate > NH_4^+-N concentration. On the basis of the RSM results, the interactive effects of these factors on the SMP formation were evaluated, and the optimal operating conditions for a minimum SMP production in such a batch activated sludge system also were identified. These results provide useful information about how to control the SMP formation of activated sludge and ensure the bioreactor high-quality effluent.

1. Introduction

Effluents from biological wastewater treatment systems contain a variety of soluble organic compounds, among which soluble microbial products (SMPs) constitute a major part of the residual chemical oxygen demand (COD) for most well-operated biological treatment systems (Schiener et al., 1998; Barker and Stuckey, 1999). SMPs are defined as the pool of organic compounds that are released into solution through substrate metabolism and microbial decay (Noguera et al., 1994; Barker et al., 2000; Aquino and Stuckey, 2004). Carbohydrates, proteins and humic substances are the main components of SMP.

SMP formation involves a very complex process with many influential factors, such as substrate type and concentration, hydraulic retention time, nutrients, temperature, solid retention time, etc (Pribyl et al., 1997; Huang et al., 2008; Krasner et al., 2009; Fernando and Allen, 2003). The contents and characteristics of SMP from different wastewater treatment reactors usually vary significantly, attributed to the different process parameters and operational conditions applied. The influences of process parameters on SMP production have been investigated using the conventional

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'change-one-factor-at-a-time' method (Barbosa et al., 2001; Eroglu et al., 1999), which requires a large quantity of experiments to yield comprehensive information. In these studies, only single influential factor was individually evaluated. This probably leads to controversial results, because the interactions between these factors could not be taken into account. For example, some researchers observed a linear increase in SMP production with the increasing influent COD concentration, while others found that there existed an optimum range of organic loads for minimized SMP production (Pribyl et al., 1997; Barker et al., 2000).

In this regard, response surface methodology (RSM) presents an alternative and more efficient approach based on statistical principles. RSM has been widely used in analyzing various biological processes, designing the experiment, building models, evaluating the effects of several factors, and searching for optimum conditions to give desirable responses and reducing the number of experiments (Oh et al., 1995; Cruz et al., 1999; Yang et al., 2003). Since many operating factors are involved in the SMP formation in wastewater treatment bioreactors, RSM can be employed as an appropriate approach to analyze the SMP formation process.

Furthermore, it is essential to understand the most significant influential parameters for SMP production. Biological systems can usually be considered as grey systems due to their high complexity and lacking of sufficiently defined or precise information. For such systems, grey relational analysis (GRA), as one of the most important contents of grey theory, has been applied extensively. The principle of GRA is to estimate the similarity and degree of the compactness among factors based on the geometric shape of the different sequences (Deng, 1989). It has been employed to evaluate the significance of the influencing factors to complex biological processes (Chen and Syu, 2003; Moran et al., 2006), and to qualitatively and quantitatively identify the interrelationships between multiple factors and variables with minimal information needed (Chou and Tsai, 2009).

Thus, this study aimed to explore the effects of substrate concentration, NH_4^+-N concentration, temperature and aeration rate on SMP production, and to find the optimum conditions for minimizing the SMP production in a batch reactor with the RSM method. Then, the GRA was used to quantitatively evaluate the significance of these influencing factors on the SMP formation. This work shall hopefully provide a useful approach for optimizing the parameters of a batch activated sludge system to minimize the SMP production and accordingly improve the effluent quality from wastewater treatment bioreactors.

2. Materials and methods

2.1. Experimental design with RSM

Based on RSM with a central composite design (CCD) as shown in Table 1, the variables X_i were coded as x_i according to the following equation:

Table 1 – Levels of the variable tested in the central composite designs.

Variable	Range and levels				
	-2	-1	0	1	2
X_1, (mg COD/L)	100	300	500	700	900
X_2, NH_4^+-N (mg/L)	15	20	25	30	35
X_3, Temperature (°C)	4	12	20	28	36
X_4, Aeration rate (m^3/h)	0.050	0.075	0.100	0.125	0.150

$$x_i = \frac{X_i - X_{i0}}{\delta X_i} \quad (1)$$

where X_i is the uncoded value of the ith independent variable ($i = 1,2,\ldots,4$), X_{i0} is the value of X_i at the centre point of the investigated area and δX_i is the step change. Substrate concentration (X_1), NH_4^+-N (X_2), temperature (X_3) and aeration rate (X_4) were chosen as the independent input variables. The effluent SMP concentration was used as the dependent output variable. The response variable was fitted by a second-order model in the form of quadratic polynomial equation:

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_i x_i^2 + \sum_{i}^{i<j}\sum_{j} b_{ij} x_i x_j (i = 1, 2 \cdots 4, j = 1, 2, \ldots, 4) \quad (2)$$

where x_i refers to input variable that influences the response variable y; b_0, b_i, b_{ii} and b_{ij} are the constant regression coefficients of the equation.

2.2. Data analysis

The parameters of the response equation and corresponding analysis of variances were evaluated using Minitab Version 14 (Minitab Inc., USA). Probability (P) values were used to check the significance of the coefficients, which are necessary to understand the pattern of the mutual interactions between the test variables. A smaller magnitude of the probability means a more significant correlation coefficient. The significance of the regression coefficient was tested by a t-test with the confidence of 95%. The quality of the fit of the polynomial model equation was expressed by the coefficient of determination (R^2), and its statistical significance was checked by an F-test. Response surface plots were generated by Matlab 7.0 (MathWorks Inc., USA). Subsequently, two additional confirmation experiments were conducted to verify the validity of the statistical experimental strategies.

2.3. GRA

To evaluate the importance of various factors on the production of SMP, independent input variables, i.e., substrate concentration, NH_4^+-N concentration, temperature and aeration rate, were chosen as the compared series and defined as:

$$z_j = \{z_j(k) | j = 1, 2, \ldots, m; k = 1, 2, \ldots, n\} \quad (3)$$

The output variable (e.g., SMP concentration) was set as the reference series and expressed as: