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Treatment of Wastewater Using Response Surface Methodology: A Brief Review

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Response surface methodology (RSM) is widely applied to gathering knowledge on the interactions among parameters that require optimization during the treatment of wastewater. It can be used to optimize parameters during the process of treating wastewater, e.g., landfill leachate. The experimental design methods are useful to evaluate the parameters involved in a treatment with the minimum number of experiments. This will reduce the need for reagents and materials for experiments, which finally causes both time and expense to be increased. Anaerobic digestion of wastewater technologies escalated depending on the design configuration of the reactor. Several important parameters are taken into consideration in designing an anaerobic reactor such as operating conditions, seed sludge, wastewater composition and mixing. To construct a highly efficient degradation system, it is necessary to optimize such effective parameters. As a result, the advanced statistical design is used for process characterization, optimization and modelling. In this paper, the fundamentals of RSM and its application in the anaerobic treatment of wastewater was discussed in brief. The various works done in an anaerobic reactor using RSM for prediction and optimization are given.

1. Introduction

Environmental pollution, specifically wastewater, is gaining attention both in the developed and developing countries (Kamyab et al., 2018). Wastewater is by-products resulted from various human activities carried out in different sectors such as manufacturing and commercial industries as well as residential buildings, which discharge significant amount of pollutants into the neighboring environment (Williams et al., 2019). In order to limit and control the contaminants released, several treatments are required prior to releasing it into the water bodies. To this end, some traditional approaches to treating wastewater has been adopted by different sectors; though, the detection of additional toxic materials and newly-emerging contaminants hinder these technologies effectiveness. According to literature, such contaminants include organic and inorganic micro-pollutants, toxic heavy metals (Rivero et al., 2017), toxic dyes, pigments, healthcare wastes and halogenated compounds, and pathogenic microorganisms (Robinson, 2017). It significantly necessitates the development of alternate options in a way to be powerful enough to cope with the above-noted issues. Recent studies on wastewater treatment technologies are being directed towards anaerobic treatment of wastewater as it is proven to be effective in treating recalcitrant pollutants (Shin and Bae, 2018) in wastewater even by using microalgae (kamyab et al., 2019). Anaerobic digestion mainly consists of three degradation phases. The first phase is hydrolysis and acidogenesis. In this phase, compounds such as lipids, proteins, and polysaccharides are degraded into soluble organic materials by hydrolytic bacteria and acidogens. Volatile fatty acids (VFA), ethanol, hydrogen and carbon dioxide are the products of this phase. These molecules will then be further converted into acetate in the acetogenesis phase. In the final phase, the acetate, hydrogen and carbon dioxide are turned to methane by methanogens (Krishnan et al., 2018). Anaerobic treatments have been proven to be effective in treating different types of wastewater such as landfill leachate (Roudi et al., 2019), municipal wastewater (Arvin et al., 2015). Different designs of anaerobic reactors had been developed by

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researchers over the years. In the early years of commercial anaerobic treatments, septic tanks and anaerobic ponds are amongst the well-known anaerobic reactors. Conventional anaerobic reactors such as up-flow anaerobic sludge bed (UASB) reactor (Selvam et al., 2019), fluidized bed reactor (Dutta et al., 2018), anaerobic sequential bed reactor, and anaerobic baffled reactor, were invented few decades later. Lastly, stage anaerobic reactor (Prasetyo et al., 2017) has also been looked into in recent years for the purpose of treating the wastewater and landfill leachate (Roudi et al., 2019). Three common design of experiment (DOE) methods are artificial neural network (ANN), multiple linear regression (MLR) (Roudi et al., 2018) and response surface methodology (RSM), with RSM being the most common in the anaerobic treatment of wastewater (Arumugam et al., 2018).
ANN was originally designed on the basis of human brain scheme. This computing system is actually a framework in which various algorithms are working together in order to process complicated data input simulating the data processing ability of the human brain (Patel and Brahmbhatt, 2016). MLR, on the other hand, is a predictive analysis to describe data and to explain the relationship between two or more controlled variables and a response (Komilis et al., 2017). In contrast to MLR, RSM is an optimizing tool which works with several controlled variables and several responses (Jha et al., 2017). Optimization of the important parameters is crucial to assure the responses are corresponding to the theories behind the experiment. In anaerobic treatment, ANN and RSM are much more favoured amongst the researchers compared to MLR. Though ANN has a better prediction analysis in another field, RSM is found to have more insightful information on the interaction between different parameters in the system of the anaerobic reactor (Venkatesh Prabhu and Karthikeyan, 2018). Thus, this paper focuses on adopting the RSM method by the latest studies conducted on anaerobic treatment of wastewater.

2. Methodology

2.1 Response Surface Methodology (RSM)

A good experimental design method is essential in studies that involve evaluating the effects of parameters in the treatment method and their intertwined relationship through minimal experiments. Generally, to have an ordinary optimization, there is a need for conducting lots of experiments, which leads to additional time and expenses in the reagents and materials for the experiments. RSM is one of the design methods capable of not only providing a large amount of information but also remains economical due to the small number of experiments performed.

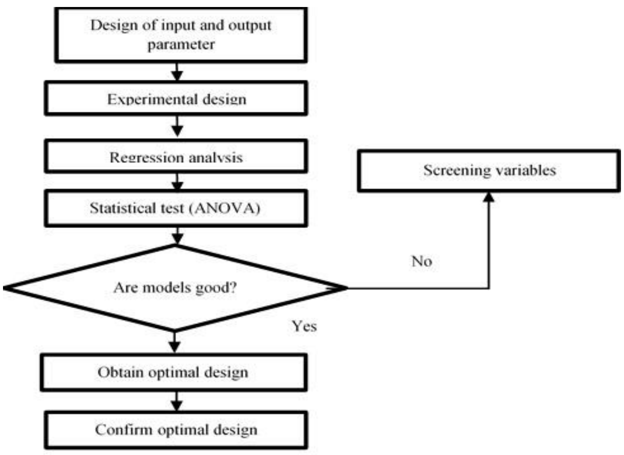

Figure 1: Mathematical modelling steps in RSM

The common mathematical modelling steps in RSM are shown in Figure 1. Generally, in any common experimental work, the most critical step is the definition of problem. Thus, to comprehend the problem more inclusively, researchers should take into consideration the entire process of the work, covering all the materials and equipment. In typical anaerobic wastewater treatment studies, possible responses could be biogas production, methane yield, COD removal and colour removal. The variables, on the other hand, are generally pH, temperature, OLR, and influent COD. Though the anaerobic process is typical, the impact of the variables on the responses varies depending on the reactor design. The next step in RSM modelling is the experimental design or building the model, where the responses are estimated and evaluated. The choice of a proper design strategy influences the response surface plot and precision of the predicted model, hence it is important to select the most fitting design strategy for the particular study (Sakkas et al., 2010). The most important design strategies commonly taken into consideration are central composite design (CCD), full factorial design (FFD), and Box-Behnken design (BBD). Different computer software has been designed to provide the use of these methods.

2.2 Full Factorial Design and Central Composite Design

As a conventional design technique, FFD sets the input variables at two or three levels. For instance, an FFD with two levels only the low and high value of each variable and presents 2k designs in case k denotes the number of variables. On the other hand, a three-level FFD considers three values which are low, middle and high, giving the number of designs for k factors as 3k. Though the three-level FFD is common, it gives a high number of the experimental run which resulted in unwanted high-order interactions. Thus, the 3k FFD offers a higher effectiveness when less than five factors are available (Sakkas et al., 2010). The disadvantage of classic FFD that is faced by many is that the models with second or higher order polynomial had difficulties to fit. As a result, in 1951, the central composite design was introduced by Box and Wilson to prevent the problems (Box and Wilson, 1951). According to Shi et al. (2019), to construct a second-order response surface model in environmental processes, most of researchers have adopted the five-level fractional design method of CCD. This technique is able to provide similar information as the three-level FFD but with a fewer number of experiments, making it a more cost-effective design method. In addition, CCD has been confirmed capable of effectively predicting the linear and quadratic interaction impacts of the factors that have effects on the selected process. The disadvantage of this technique is that it requires a high amount of time to work and it takes into account too many factors. Three-point types are required for this design method: cube points (which are obtained from factorial design), center points and axial points. Thus, Eq(1) can be used to determine the total number of experiments required:

$$\text{Total Number of Experiments} = 2k + 2k + C0 \quad (1)$$

where k stands for the number of factors, 2k denotes the cubic runs, 2k is the axial runs, and C0 signifies the center point's runs.

2.3 Box-Behnken Design

As another alternative to the time consuming FFD, Box and Behnken developed a technique for a three-level variable that are evenly spaced (Box and Behnken, 1960). The number of experiments required in this design method has been decreased as much as possible in a quadratic model fitting; and the use of the second order polynomial model can return higher quality results in terms of precisely describing the linear relationships and quadratic impacts. Eq(2) is able to calculate the total number of experiments required:

$$\text{Total Number of Experiments} = 2k(k-1) + C0 \quad (2)$$

where k stands for the number of factors and C0 signifies the number of center points.

3. Results and Discussion

Table 1 shows the overview of work performed in the anaerobic reactor using RSM as the prediction model. Kainthola et al. (2018) used a batch reactor to treat a co-digestion of rice straw and hydrilla verticillata. The variable factors that affected the responses are C/N ratio, F/M ratio and pH. From the RSM-CCD results, the optimal condition was C/N ratio 29.7, F/M ratio 2.15 and pH 7.34. The inhibitory effect of ammonia and VFAs and unbalanced nutritional structure of rice straw are improved by optimizing the C/N ratio and F/M ratio in the co-digestion which resulted in higher methane yield. It was proven that RSM can play a significant role in the determination of the optimal condition in the co-digestion of rice straw and hydrilla verticillate. In another study by Mortezaei et al. (2018), a hybrid expanded granular sludge bed and fixed-bed (EGSB-FB) bioreactor were used. Similar to Kainthola et al. (2018), this study also used RSM and CCD as an optimization technique. The optimum region of the hybrid EGSB-FB reactor was acquired at influent COD of 11,200 mg/L, HRT of 27h, and COD/N ratio of 51. The use of the above-noted variables led to a 90% COD removal efficiency. Although there are three selected parameters, COD influent and COD/N ratio were determined to be the more influential parameters.

In contrast to the works mentioned above, Safari et al. (2018) conducted a study using Box-Behnken design. As Box-Behnken design is advisably used for three or more factors experiment, the study was performed with four factors; temperature, stirring time, totally solid and inoculum ratio. The most influential parameter in the study was found to be the temperature. The temperature affects the methane generation, where the emission rate of methane is reduced rapidly when the reactor surpasses a certain temperature (52.4 °C in thermophilic and 40.36 °C in mesophilic conditions). RSM was found effective in predicting the methane emitted from co-digestion of cattle manure, inoculum, and canola residues.

An innovative modified anaerobic sequential batch reactor (MASBR) was used to treat the textile dyeing industry wastewater. The study conducted by Rajasimman et al. (2017) combined anaerobic degradation and adsorption processes in removing the dyes in the textile industrial wastewater. This study found a new approach in using ground nutshell powder as the absorbent for the dye and Fujino spirals as the biomass support in the MASBR. The quantity of both the absorbent and the biomass support were optimized by the CCD and the response parameters were predicted using RSM. Rajasimman et al. (2017) studied three important response parameters, which are decolourization, COD reduction and sludge volume index (SVI). The differences in the experimental and predicted response value by RSM were less than five percent, proving RSM is a dependable tool for designing an experiment. An unconventional approach introduced by Jacob and Banerjee (2016) in dealing with acidification problem of anaerobic treatment of potato waste applies the CCD-RSM method for optimization of parameters. Jacob and Banerjee (2016) suggested a co-digestion of potato waste and aquatic weed to resolve the low pH in anaerobic treatment of potato waste resulted from the accumulation of volatile fatty acid. The target response for the study is to increase the methane yield from anaerobic process. Sathish and Vivekanandan (2016) took a different approach opposed to other studies listed in Table 1 by analyzing the effects of four variables instead of the usual three using CCD.

Table 1: Overview of work carried out in anaerobic reactor using RSM

Anaerobic Reactor	Type of wastewater	Method	Runs	Dependant Variables	Independent variables
Batch reactor (Kainthola et al.,2018)	Rice straw *hydrilla verticillata*	CCD	20	x_1=C/N ratio x_2= F/M ratio x_3= pH	y_1=methane yield
Hybrid EGSB-FB bioreactor (Mortezaei et al., 2018)	Yogurt effluent	CCD	19	COD influent	HRT
Batch reactor (Safari et al., 2018)	Cattle manure and canola residues	Box-Behnken	29	Temperature	Stirring time
MASBR (Rajasimman et al., 2017)	Textile wastewater	CCD	13	Sorbent dosage	Biomass support
Batch reactor (Banerjee, 2016)	Potato waste and aquatic weed	CCD	20	x_1= Total solid x_2= Proportion of co-support x_3= Inoculum concentration	Methane yield
Floating drum anaerobic digester (Sathish and Vivekanandan et al.,2016)	Rice straw	CCD	30	x_1= Temperature x_2= pH x_3= Substrate concentration	Biogas yield
Mixed plug-flow reactor (Rasouli et al., 2015)	Cow manure	CCD	18	x_1= OLR x_2= Temperature x_3= Mixing level	y_1= Biogas production y_2= Methane yield
Batch reactor (Sajeena et al., 2014)	Organic fraction municipal solid waste	CCD	20	x_1= pH x_2= Substrate concentration x_3= TOC	Biogas production

Thus, based on Eq (1), the number of runs is slightly more than other studies. A mixed plug-flow reactor is used in a study by Rasouli et al. (2015) for the treatment of cow manure. This study concentrates on the biogas production and methane yield from the anaerobic treatment. Three important parameters are taken into consideration to improve and optimize both of the target output. On the other hand, Sajeena et al. (2014) looked into the optimum condition that should be provided for anaerobic treatment of organic fraction municipal solid waste by utilizing RSM. CCD method is used to determine the significance of process parameters such as pH, substrate concentration and total organic carbon (TOC) on the biogas production. It was discovered that both the pH and substrate concentration anaerobic from the organic fraction of municipal solid waste through anaerobic digestion. RSM was used for the aim of predicting the behavior of influent COD, up-flow velocity (Vup) and HRT in the bioreactor. Since the experimental results were approximately close to the predicted values, it demonstrated that the CCD-RSM technique was applicable in optimizing the bio-hydrogen producing process.

4. Conclusions

The review performed for the purpose of this study indicated that experimental design has been extensively applied to various types of anaerobic treatment through a variety of factorial and optimization designs. In addition, it was confirmed that RSM is successful in designing, modelling, predicting, and optimizing the anaerobic digestion processes with a desirable level of precision. From amongst various RSM design strategies, e.g., CCD, BBD, and FFD, the first item succeeded to receive the most attention of researchers in this field of study. Majority of scholars have examined four or fewer factors and the predominant ones in most of the anaerobic reactors were methane yield, biogas production rate and COD removal with methane yield being the most popular response. The optimization capacity and design of the strategies (other than CCD) are required to be further investigated in a way to explore more accurately their appropriate applications, for instance, the use of BBD strategy in experiments with numerous factors. RSM has shown a high capacity of modelling and optimizing more than four effective factors, which can achieve the results of higher levels of meaningfulness and comprehensiveness. This study showed the need for examining other responses alongside the methane yield, including cost and removal of toxic pollutants (for example, dyes and heavy metals).

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