Development of Mathematical Model for BOD Removal Efficiency

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A study was conducted on anaerobic digestion of distillery effluent under varying organic loads using cowdung as the seed material. The BOD removal efficiency reached a maximum of 94.6 per cent and the biokinetic constants were evaluated using modified Monod's equations. A mathematical model was developed using multiple linear regression technique for the prediction of BOD removal efficiency and the analysis of the data, according to the developed model which gave a maximum deviation of ± 4.4.

Introduction

Bio-ethanol is mainly produced by the fermentation of distilled sugarcane molasses solution. After fermentation, alcohol is separated by distillation and the residual liquor is discharged as distillery spentwash or effluent. The effluents, as such discharged from the plant is hot, highly coloured (dark brown), acidic and possess an objectionable odour. The BOD value is extremely high. Likewise the values of suspended solids, dissolved solids, chlorides, sulphates, and nitrogen are also too high. The potassium content of the effluent is used for irrigation. Though distillery effluents do not contain any toxic substances, these create toxic conditions in the receiving stream by immediate depletion of dissolved oxygen resulting in massive fish kills, destruction of flora and fauna, production of foul odours, and discoloration of streams. Most of the distilleries stagnate their effluents on lands as ponds. This type of stagnation is not a good practice as there are chances of seepage and subsequent ground water pollution. Further, obnoxious odour spreads to a few kilometers which is a cause of serious health problem.

The anaerobic metabolism of complex substrate can be regarded as a three step process, namely: (a) Hydrolysis of suspended and soluble organics, (b) Degradation of small organic molecules to various fatty acids and ultimately to acetic acid, and (c) Formation of methane, primarily from acetic acid, and also from hydrogen and carbon dioxide. In a multistep process, methane fermentation, the slowest step will govern the overall kinetics of waste stabilization. The relationship between residual concentration of limiting substrate and bacterial growth rate was given by Monod in 1949.

Vaidyanathan\(^1\) has studied the treatability of predigested distillery wastewater diluted with domestic sewage and found that the BOD removal efficiency increased with increase in dilution. Vaidyanathan\(^2\) has also carried out studies on the treatment of predigested distillery effluent and evaluation of bio-kinetic coefficients in an activated sludge process and reported a BOD removal efficiency 85 to 90 per cent. Gokuldas\(^3\) conducted a study on the two stage anaerobic digester to treat distillery waste and observed that the overall BOD removal efficiency was 92.8 per cent and COD 81.7 per cent. Harada\(^4\) has studied the feasibility of thermophilic anaerobic treatment of an alcohol distillery effluent using UASB reactor. Ciftic and Oztrak\(^5\) have studied the anaerobic aerobic treatment plants in fermentation industry producing bakers yeast from sugar beet molasses and observed that an average COD removal was 75 per cent in the mesophilic anaerobic stage with a daily biogas production rates,
as high as 20,000 m$^3$/d. Phade$^4$ have conducted a study on the effects of redox potential in a thermophilic laboratory scale two stage anaerobic digester to treat distillery effluent and observed that about 90 percent COD removal was achieved with a gas production of 0.4 L/g COD.

A comprehensive review of the methods for handling distillery effluent showed that the effluents from such plants are generally high in both, dissolved organic and inorganic materials, posing particular treatment difficulties. Although several treatment procedures are being used or have been proposed, there is no widespread agreement on the most suitable methods. Also, information on the design of treatment plants based on biokinetic parameters for distillery effluent, is very limited, the study determines the biokinetic parameters which enable us to describe the metabolic performance of the microorganisms when fed with the substrate and other components in the distillery treatment processes.

### Experimental Procedure

All chemicals used during digestion and for analysis were of AR grade. The reactor was a wide mouthed glass bottle of 5 L capacity. Necessary tubes were connected to facilitate addition of influent, for removing treated effluent and settled solids and for gas transfer. The gas collection apparatus composed of a glass bottle of 500 mL capacity and another levelling bottle of 1 L capacity for the water displaced from the gas bottle. The reaction was carried out in the air tight container for effective anaerobic digestion and at a temperature of 28°C. Cowdung was used as the seed material and about 2 L of the distillery effluent was mixed in the digester and allowed to stand till gas evolution was noticed. Initially the sludge was not wasted in order to allow the MLSS concentration to build up to the desired level in the reactor. Once a day, the sludge was wasted from the reactor and the wasted volume was replaced with distilled water. The influent was added in terms of BOD load at regular interval of 24 h and the digestion was carried out until stabilized condition was achieved as represented by sludge growth on a day-to-day basis and the effluent BOD remained constant. The pH of the contents in the reactor was maintained between 6.7 to 7.3 which is effective for anaerobic biological growth. Calculated amount of diammonium phosphate and urea were added to the feed solution to maintain the BOD : N : P ratio as 100 : 2.5 : 0.5.

### Results and Discussion

The distillery effluent collected from a distillery unit was analysed and the results are given in Table 1. The effluent was found to have an acidic pH of 4.2 with a high amount of total solids. The BOD and COD values were found to be 10440 and 15660 mg/L giving a BOD/COD ratio of 0.7 which indicated that the effluent was highly amenable for biological digestion. The anaerobic digestion of distillery effluent was carried out with varying organic loading rates from 100 to 600 mg/L and the results are given in Table 2. The optimum organic load required for the maximum removal of BOD and COD of the effluent was determined and it was observed that the BOD and COD removal reached a maximum of 94.6 per cent and during the digestion the mean cell residence time $\bar{t}$ was varied by operating the reactor at varying food to microorganism ratio ($U$) by varying the MLVSS concentration. Results indicated that BOD and COD removal efficiency decreases with decrease in mean cell residence time $\bar{t}$ and decrease with increase in F/M ratios.

From the experimental results obtained at different organic loading rates for BOD and suspended
Table 2—Anaerobic digestion of distillery waste with varying organic loads

<table>
<thead>
<tr>
<th>Organic load (mg/L)</th>
<th>Effluent BOD (mg/L)</th>
<th>MLVSS (mg/L)</th>
<th>Hydraulic retention time (d)</th>
<th>BOD removal efficiency, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1830</td>
<td>3090</td>
<td>3.45</td>
<td>82.47</td>
</tr>
<tr>
<td>200</td>
<td>1590</td>
<td>3180</td>
<td>4.10</td>
<td>84.77</td>
</tr>
<tr>
<td>300</td>
<td>1160</td>
<td>3290</td>
<td>3.97</td>
<td>88.89</td>
</tr>
<tr>
<td>400</td>
<td>850</td>
<td>3370</td>
<td>3.83</td>
<td>91.86</td>
</tr>
<tr>
<td>500</td>
<td>680</td>
<td>5080</td>
<td>3.85</td>
<td>93.49</td>
</tr>
<tr>
<td>600</td>
<td>570</td>
<td>5530</td>
<td>3.87</td>
<td>94.54</td>
</tr>
</tbody>
</table>

solids removal, the substrate removal rate constant ($k$), half velocity coefficient ($K_s$), decay coefficient ($K_d$), yield coefficient ($Y_c$) and the maximum specific growth rate ($\mu_{max}$) were determined using Monod’s kinetic equations:

$$\frac{X \theta}{S_o - S_e} = \frac{K_s}{k} \frac{1}{S_e} + \frac{1}{k}$$

In Eq.(1) the term $X \theta /S_o - S_e$ was plotted against $1/S_e$. The intercept of the plot equals $1/k$ whose reciprocal gives the value of $k$. The slope of the plot equals $K_s/k$. By multiplying slope and $k$, the value of $K_s$ could be obtained.

The coefficients $Y_c$ and $K_d$ were determined by plotting the terms $1/\theta$ against $U$ (ie $S_o - S_e/X \theta$).

The intercept of the plot gave the value of $K_d$. Slope of the plot equals $Y_c$ from [Eq.(1)].

$$\frac{1}{\theta} = Y_c U - K_d.$$ \hspace{1cm} \ldots (2)

The coefficient $\mu_{max}$ was obtained by multiplying the coefficients $Y_c$ and $k$. The biokinetic coefficients were evaluated using modified Monod’s equations and are given in Table 3. The rate of substrate utilization was found to be higher at the early stages of digestion throughout the process and the reason for the initial high substrate utilization rate may be due to the adsorption of soluble substrates by the bacteria and extracellular slime. The subsequent drop in rate, following the initial high rate may be interpreted as saturation of adsorption sites.

The subsequent rate increase may be attributed to continued increase in metabolic activities caused by cell growth. Adsorption and metabolism occur concurrently.

The value of the substrate removal rate indicated the hydraulic retention period actually required for complete waste stabilization to occur. The half velocity constant, $K_s$ which indicates the substrate concentration at onethalf of the maximum specific utilization rate was found to be significant. The decay coefficient value indicated that a relatively large proportion of biodegradable organic waste has been synthesized into new cells. Factors which contribute to the decrease in observed yield as mean cell residence changes are maintenance energy, cell death and lysis, cryptic growth, formation of extracellular polymers, predator activities and predominance of different microbial species with different energetic characteristics. The yield coefficient, obtained in the present investigation, was found to be higher than the value reported in the literature, which might be attributed to the higher concentration of hydrolysable carbohydrates in the effluent.

Development of Mathematical Model

While many formulae can be used to ascertain the relationships among more than two variables, the most frequently used method is that of linear equations. The multiple linear regression takes the following form:

$$Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + \ldots + b_x X_x.$$ \hspace{1cm} \ldots (3)

In the present investigation, the multiple linear regression technique has been used to predict the
BOD removal efficiency using the biokinetic parameters.

If \( X_1 \) and \( X_2 \) are substituted with biokinetic constants, then,

\[
X_1 = \frac{k}{K_s \cdot Q} \cdot V \cdot X,
\]

and
\[
X_2 = \frac{BOD_{\text{influent}}}{BOD_{\text{influent}}},
\]

where, \( k = \) Substrate removal rate constant (d\(^{-1}\)), \( K_s = \) Half -velocity constant (mg/L), \( V/Q = \) Hydraulic retention period (d) and \( X = \) Mixed Liquor volatile suspended solids (mg/L).

Substituting \( X_1 \) and \( X_2 \) in Eq.(3), the Y, BOD removal efficiency takes the form,

\[
Y = a + b_1 \cdot \frac{k}{K_s \cdot Q} \cdot V \cdot X + b_2 \cdot \frac{BOD_{\text{influent}}}{BOD_{\text{influent}}},
\]

The constants \( a, b_1, \) and \( b_2 \) are determined by the methods of least squares by solving the systems of equations.

\[
\begin{align*}
\sum Y &= na + b_1 \cdot \sum X_1 + b_2 \cdot \sum X_2, \\
\sum X_1 \cdot Y &= a \cdot \sum X_1 + b_1 \cdot \sum X_1^2 + b_2 \cdot \sum X_1 \cdot X_2, \\
\sum X_2 \cdot Y &= a \cdot \sum X_2 + b_1 \cdot \sum X_1 \cdot X_2 + b_2 \cdot \sum X_2^2.
\end{align*}
\]

The constants \( a, b_1, \) and \( b_2 \) are evaluated by taking data of the present study under varying organic loads. The data used for the estimation of multiple regression coefficients are presented in Table 4. The regression coefficients \( a, b_1, \) and \( b_2 \), evaluated are given here:

\[
a = 77.83, \quad b_1 = 0.976, \quad b_2 = 0.970.
\]

Hence the proposed model for the prediction of BOD removal efficiency is given by the Eq.(7).

\[
Y_{\text{out}} = 77.83 + 0.976 \cdot \left[ \frac{k}{K_s \cdot Q} \cdot V \cdot X \right] + 0.97 \cdot \left[ \frac{BOD_{\text{influent}}}{BOD_{\text{influent}}} \right],
\]
The analysis of the data on anaerobic digestion of distillery effluent according Eq.(7) is shown in Table 5 which gave a maximum deviation of ± 4.4. Thus the results of the present study on the prediction of BOD removal efficiency using multiple linear regression technique has been successfully arrived at a model for anaerobic digestion process of distillery effluent.

Conclusions
The distillery effluent is found to be highly suitable for anaerobic treatment as indicated by COD/BOD ratio. A significant BOD removal is achieved in the present study which may be due to the application of fresh cowdung as the seed material. The results on the prediction of BOD removal efficiency using multiple linear regression technique has been successfully arrived at a model for anaerobic digestion of distillery effluent.

Notations
\( k \) = Substrate removal rate constant, \( d^{-1} \).
\( K_s \) = Half velocity constant, mg/L.
\( Y_c \) = Yield coefficient.
\( K_d \) = Decay coefficient, \( d^{-1} \).
\( \mu_{	ext{max}} \) = Maximum specific growth rate of microorganisms, \( d^{-1} \).
\( d \) = Hydraulic retention time, day.
\( \theta \) = Mean cell residence time, mg/L/d.
\( S_0 \) = Influent BOD, mg/L.
\( S_e \) = Effluent BOD, mg/L.
\( X \) = Mixed liquor volatile suspended solids (MLVSS) representing concentration of microorganisms in reactor, mg/L.

References