

# FUZZY RULE BASED APPROACH FOR MODELING BIOGAS PRODUCTION RATE IN A REAL SCALE UASB REACTOR TREATING DISTILLERY WASTEWATER

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## ABSTRACT

The high rate anaerobic biological processes are used for treatment of industrial wastewater and these processes are subjected to many disturbances due to variation in quantity and quality of wastewater. Many uncertainties are involved in their operation, control and measurement of parameters. A fuzzy model is developed for prediction of biogas production rate in a real scale UASB reactor treating distillery wastewater. The parameters used for daily monitoring and operation of the plant (flow rate, influent COD, effluent COD, pH, temperature and biogas production rate) are used for model development. The performance of the model was evaluated using statistical parameters. The correlation coefficient (R value) of 0.9039 and Root Mean Square Error (RMSE) of 3250.59 was observed indicating good agreement between the predicted values and the observed values of biogas production rate. The model will be useful for assessment of performance of the real scale UASB reactor treating distillery spent wash and also to control the operation of the plant.

**Key Words :** UASB reactor, Spent wash, COD, Fuzzy Model, Biogas, Organic Loading Rate, Hydraulic Loading Rate

## INTRODUCTION

Distilleries are one of the most polluting industries, producing very strong wastewater called spent wash during the alcohol production. The combination of biomethanation and biocomposting is a popular choice for treatment of the spent wash<sup>1</sup>. Up flow Anaerobic Sludge Blanket (UASB) reactors are used for biomethanation and treatment of distillery wastewaters due to their simplicity in operation and stability compared to other processes. The performance of these processes fluctuates with many parameters like flow, composition, organic loading rate, pH, and temperature. This results into fluctuation in the output such as biogas production rate and effluent

composition.

Mathematical models of biological wastewater treatment systems provide useful tool for simulation, control of system operation and investigate certain engineering questions without time consuming and expensive laboratory test<sup>2</sup>. Up flow Anaerobic Sludge Blanket (UASB) reactors using the mathematical model it is possible to predict the performance of the reactor such as biogas production rate, Effluent Chemical Oxygen Demand (COD<sub>ef</sub>) and Effluent Volatile Suspended Solids (VSS). However to develop a mathematical model for anaerobic treatment process like UASB is very difficult because the anaerobic treatment methods are very sensitive and complex in operation. The performance of these processes varies significantly with different reactor configurations, influent characteristics and

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operational conditions. This requires detailed process knowledge, determination of kinetics parameters and details of stoichiometric knowledge of microbial reactions occurring in the treatment process. Solution of these models is very complicated because many mathematical equations and parameters are involved.

The soft computing techniques are now widely used for modeling and controlling the operations of wastewater treatment processes particularly the high rate anaerobic processes such as UASB reactors. Neural networks are structures capable of universal computation where knowledge and functions are distributed among the nodes each performing some simple nonlinear computation. They can be given training set based on examples of unknown input output relations of the system for which modeling is required<sup>3</sup>. The Artificial Neural Network (ANN) models are black box in nature and its relationship between inputs and outputs are not easily interpreted<sup>4</sup>. Genetic algorithms are general adaptive search method based on the main ideas of Darwinian evolution. Fuzzy logic brings formalism with its own syntax and semantics capable of expressing qualitative knowledge about problem under study. Its excellence relies specially in the strength of its interpolative reasoning mechanism<sup>4</sup>. Fuzzy logic presents flexibility and tolerance with imprecise data. Fuzzy logic can be built on top of human experience, combining natural language in an easy to understand way and also being able to model complex nonlinear functions<sup>5</sup>.

#### Literature review

Soft computing techniques such as Fuzzy Logic (FL), Genetic Algorithms (GA), Neural Network (NN) and hybrid systems are found to be useful for the advanced control, diagnosis and modeling of nonlinear and complex systems. The biological treatment methods particularly anaerobic processes are widely used for treatment of high strength wastewater. Biological wastewater treatment processes are very complex and difficult to operate due to many uncertainties involved in measurement and control of operation. Fuzzy logic is becoming very common for intelligent control of these processes<sup>6-9</sup>. Fuzzy controller can be constructed using linguistic rules designed on the basis of expert's knowl-

edge. Fuzzy IF-THEN rules were used to build a model for predicting the coli form removal efficiency in a slow sand filter<sup>10</sup>. The fuzzy rule based modeling provided a comprehensive approach for performing risk analysis and satisfactory prediction was obtained from the model. Fuzzy modeling offers a powerful tool to describe complex nonlinear systems such as biological processes<sup>2,11</sup>. A knowledge based fuzzy controller was developed<sup>12</sup> for controlling aeration process in a pilot scale Sequencing Batch Reactor (SBR) plant. The fuzzy controller reduced the complexity in operation and controlled the operation of SBR.

To monitor and control biological processes, online measurements of the living part of the system are necessary which is difficult and expensive. Polit et al. (2001) developed the fuzzy estimator based on Takagi-Sugeno model<sup>13</sup>. The estimator determines the total and partial alkalinity of the influent, the concentration of the substrate at the input, and the volatile fatty acid from the online measurement. Four input variable and five output variables were used in developing the estimator. Takagi-Sugeno structure with trapezoidal membership functions were used for construction of the rule base. The quantity of fuzzy subset for each input variable was determined by variation domain in the experimental data. The fuzzy toolbox of MATLAB was used to build up the fuzzy estimator. The fuzzy estimator was built on the basis of online measurement of  $Q_{in}$ ,  $Q_{gas}$ , and pH. The predicted values of effluent partial and total alkalinity and VFA at the output of the reactor follow quite well with the measured values. These quantities are difficult to measure online but are useful in the process knowledge. A fuzzy dynamic model was developed<sup>14</sup> to predict output of gas flow rate for an anaerobic digester. The fuzzy coefficient was determined using fuzzy model for various conditions of pH and temperature. The kinetic growth rate constant was modified by multiplying it with fuzzy coefficient. The growth rate constant is required to determine substrate utilization rate and hence biogas production rate.

A new approach to nonlinear modeling and adaptive monitoring using Fuzzy Principal Component

Regression (FPCR) is proposed<sup>15</sup> and applied to a real scale wastewater treatment plant. The FPCR method was used to predict the output variable, the reduction of chemical oxygen demand in the full scale Waste water Treatment Plant (WWTP). The model was successful in modeling nonlinear process and predicted the COD reduction under multiple operating conditions. Stability is a critical factor in evaluating anaerobic treatment systems. The industrialization feasibility of an anaerobic system is highly dependent upon its stability<sup>16</sup>. The stability of a high rate anaerobic system is conveniently evaluated by considering the response of some system parameters against overloading and toxic substances. Effluent quality, gas production and composition are mostly focus of monitoring. The experimental stability study showed that the response of the system parameters subjected to system disturbance is very complex and difficult to analyze. Based on fuzzy method, a fuzzy stability index N was proposed<sup>16</sup> to integrate the complex information contained in various individual system parameters. The instability of certain system subjected to a certain shock could be explicitly revealed by its variance of N. This method of fuzzy stability index N was found to be more convenient compared with direct examination of the reactor's performance.

Wastewater treatment plants (WWTP) control and prediction under wide range of operating conditions is an important goal in order to avoid breaking of environmental balance, keeping the system in stable operating conditions and suitable decision making<sup>3</sup>. Due to the high complexity of WWTP processes and the heterogeneity, incompleteness and imprecision of WWTP data, finding suitable model poses substantial problems. The fuzzy time delay neural networks<sup>3</sup> were used to characterize the time variation of outgoing variables. Experimental results show that the networks are able to characterize WWTP behavior in statistically satisfactory sense. The biological treatment processes particularly anaerobic processes are very sensitive to the overloads and fluctuation of input parameters and therefore complex in operation. Fuzzy logic is used for predicting state of the reactor, fault detection and isolation and control of operation<sup>17,18</sup>. A fuzzy-logic-based diagnosis system was developed for deter-

mination of the acidification states of an anaerobic wastewater treatment plant<sup>5</sup>. The diagnosis system was based on expert's knowledge to determine the acidification state of the process. The expert system was implemented as a rule base in MATLAB fuzzy logic tool box. The results obtained showed the capacity of the system to determine anomalies in the operation of the bioreactor, establishing the current acidification state within a range between normal and overloaded.

Fuzzy modeling techniques are suitable for nonlinear systems like anaerobic treatment process. Many factors can affect the performance of the system, such as system configuration, influent composition, and environmental conditions. Performance of a fuzzy model depends on the optimum number of fuzzy IF-THEN rules required to describe the system, type and number of membership functions in each rule. To decide the rule base expert's knowledge, opinion of plant operator and trend of the past data is necessary, which is a tedious process. Adaptive Network based Fuzzy Inference System (ANFIS) which combines the merits of fuzzy logic and neural networks is now a days used for modeling biological wastewater treatment processes.<sup>2,11,16</sup> However huge data is necessary for ANFIS modeling and the type and number of membership functions, number of rules is automatically determined by ANFIS depending on the data used for training. In case of fuzzy modeling, it is more convenient to incorporating expert knowledge in model development<sup>3,7,9,10</sup>.

The spent wash is a very strong wastewater with COD of 90000-120000 mg/L and it is generated during alcohol production from sugar cane molasses in the distilleries<sup>1</sup>. The typical characteristic of spent wash can be found in the literature.<sup>1,19</sup> The spent wash is treated by using the combination of anaerobic and aerobic biological treatment processes.<sup>19</sup> The anaerobic treatment to the spent wash is generally given by UASB reactors. If any system disturbance such as organic overload etc occurs, it affect the performance of the reactor in terms of the biogas production and effluent COD. A mathematical model of the system helps to understand the behavior of the system under various operating conditions and also useful for control of the system. Many attempts are found in literature for modeling of real scale

wastewater treatment plant,<sup>3,15,20</sup> particularly aerobic processes such as activated sludge process. Many attempts<sup>2,11,21-23</sup> were found for modeling anaerobic treatment systems such as UASB reactor, Anaerobic Fluidized Bed Reactor (AFBR) and Anaerobic Expanded Bed Reactor (AEBR) treating different types of wastewater; however no attempt is found for modeling a real scale UASB reactor treating distillery wastewater. An attempt is made to develop a fuzzy rule based model to predict biogas production rate for a real scale UASB reactor treating distillery wastewater using some of the important parameters used for routine monitoring and controlling the operation of the plant.

## MATERIAL AND METHODS

For development of the fuzzy model, the operational data was collected for a WWTP of a distillery located near Nashik.

### Description of waste water treatment plant

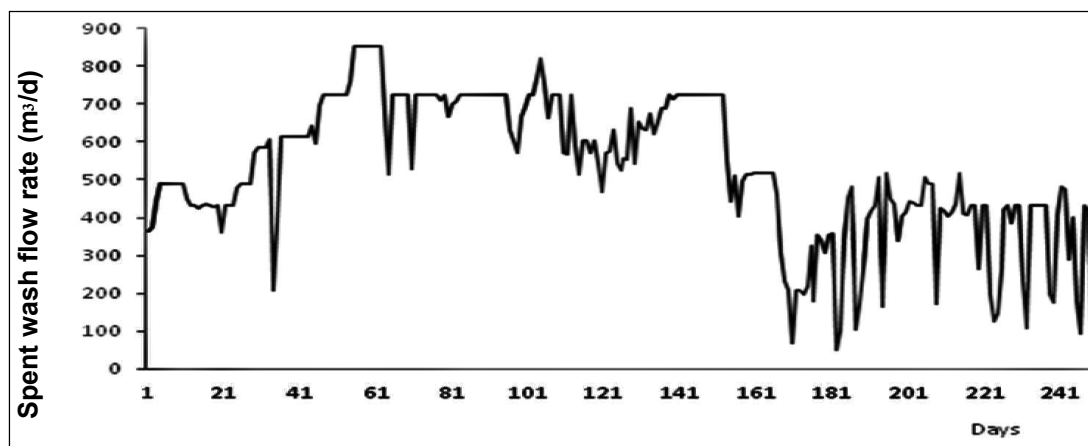
The wastewater treatment plant consists of anaerobic treatment using UASB reactor and aerobic composting of treated effluent. The treatment flow sheet is shown in **Fig. 1**. The wastewater treatment plant consists of different units like buffer tank, four UASB reactors ( $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  working in parallel), gas holder and various pumps and other machineries. During the treatment of the spent wash in the UASB reactor, about 60-70% COD is converted into biogas with methane content varying from 65-70%. Due to high calorific value, it is used for running the

boilers. The treated spent wash is taken to aerobic composting along with bagass to produce compost. As pH is increased during the anaerobic treatment of spent wash in the reactor and the pH of raw spent wash is generally 3-4.5 which is very low, therefore part of treated effluent is recycled and mixed along with raw spent wash in the buffer tank. The recirculation ratio used varies from 2 to 3 and it depends on the pH and temperature of influent spent wash. The recirculation of treated effluent causes dilution of spent wash and it results into lowering COD and increase of pH. The diluted spent wash is then pumped at the rate of 110 m<sup>3</sup>/h with the help of two feeder pumps in parallel. The spent wash feeding to the reactors was carried out at the rate of 25 m<sup>3</sup>/h to reactors  $R_1$ ,  $R_2$ ,  $R_3$  and at 35 m<sup>3</sup>/h to reactor  $R_4$ .

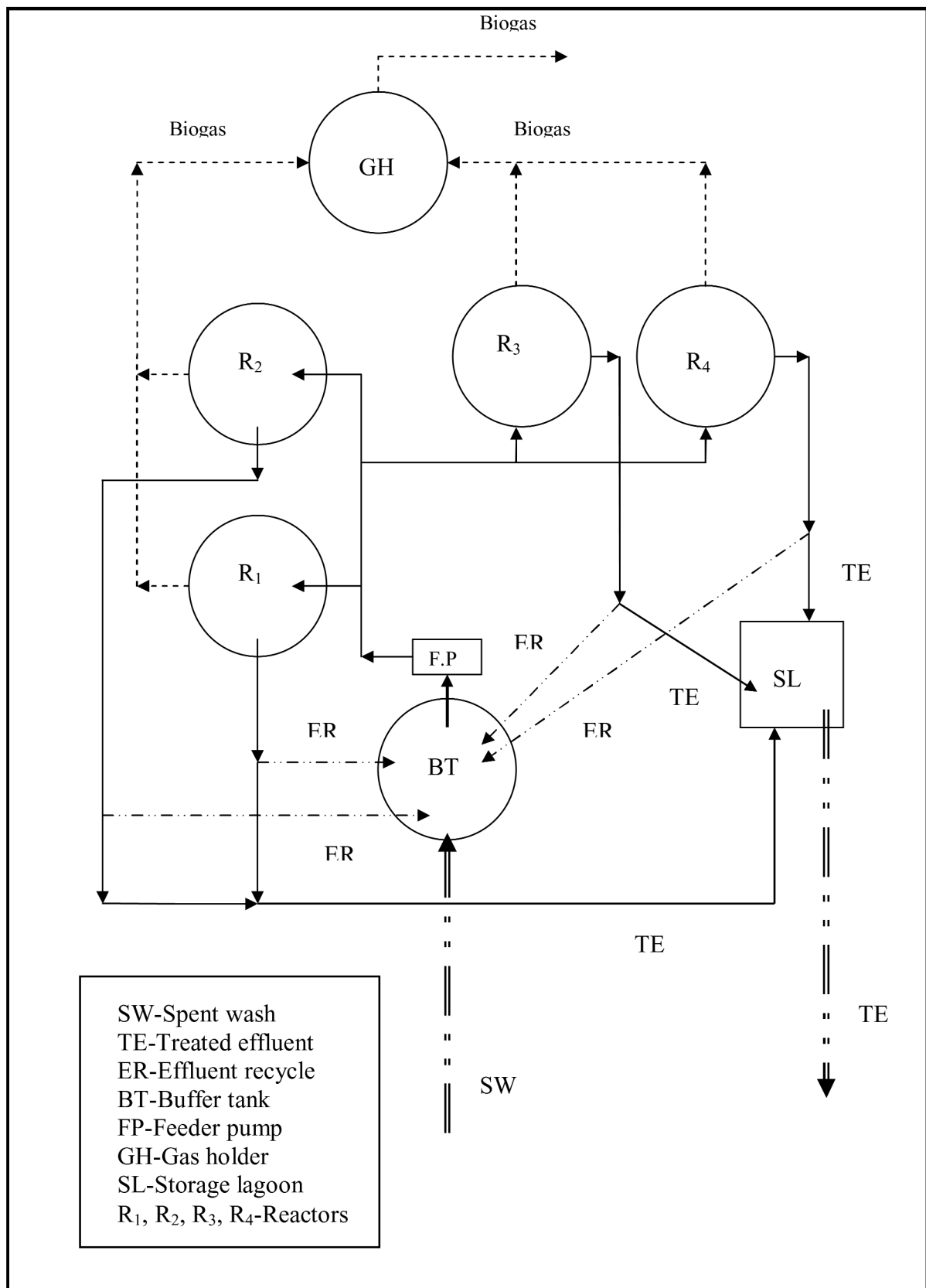
## RESULTS AND DISCUSSION

### Data Collection

The parameters like flow rate, temperature, pH, COD of raw spent wash are measured as input parameters to the reactor and temperature, effluent pH, effluent COD, VFA and alkalinity of treated spent wash are measured as output parameters during daily monitoring of the plant. The parameters pH, temperature and spent wash flow rate and Biogas production rate are measured online and remaining parameters are measured offline. The pH and temperature of the diluted spent wash in the buffer tank is also recorded daily. The daily variation in spent wash flow, influent COD, pH, Temperature, Biogas production rate and effluent COD observed during



**Fig. 2 :** Variation in spent wash flow rate.



**Fig. 1 :** Layout of wastewater treatment plant.

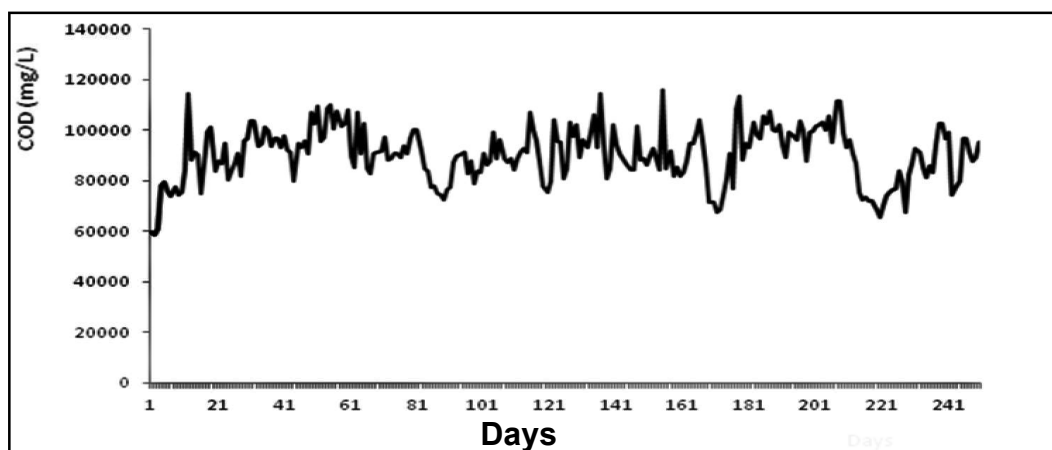


Fig. 3 : Variation in COD of influent spent wash.

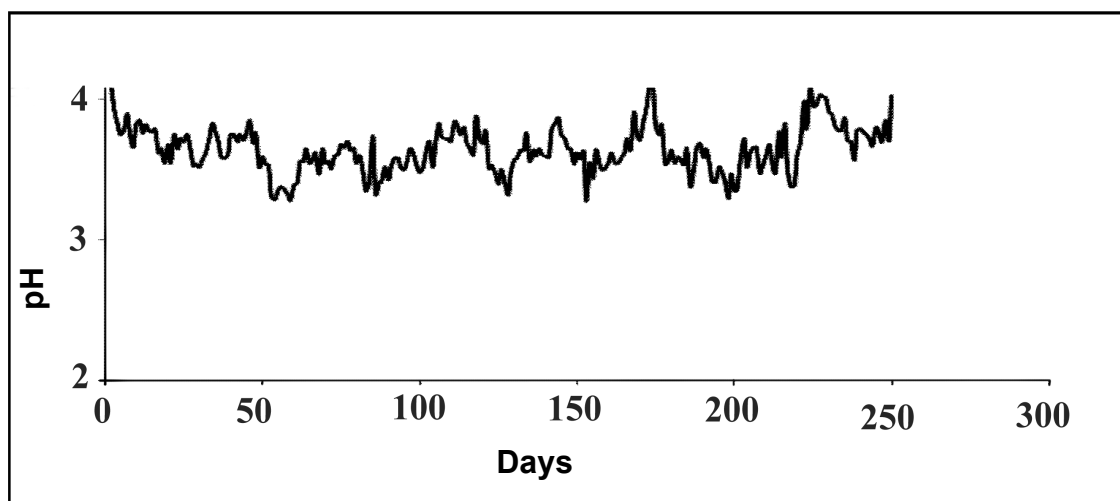


Fig. 4 : Variation in pH influent spent wash.

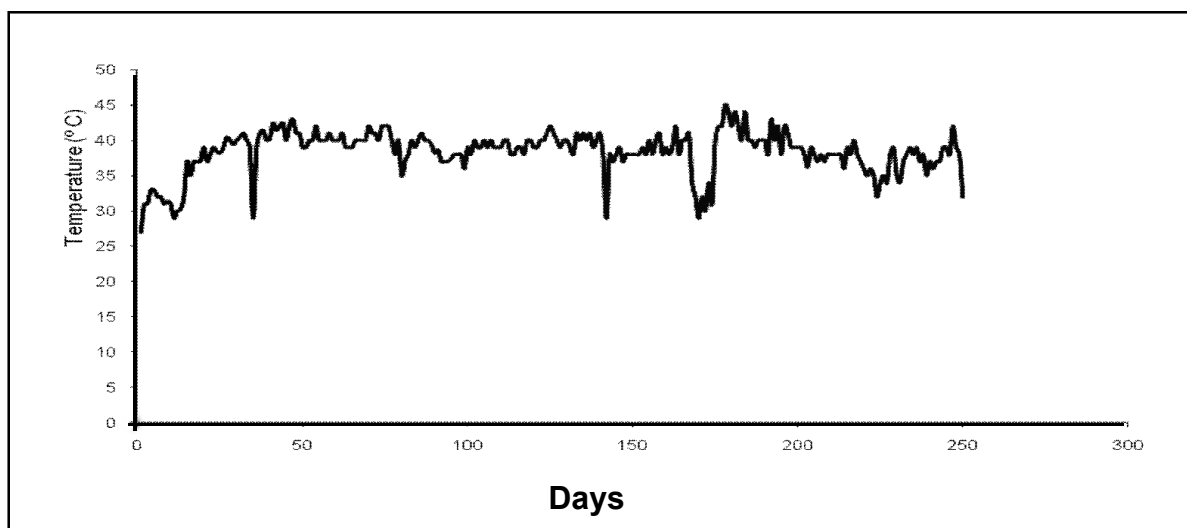


Fig. 5 : Variation in temperature of influent spent wash.

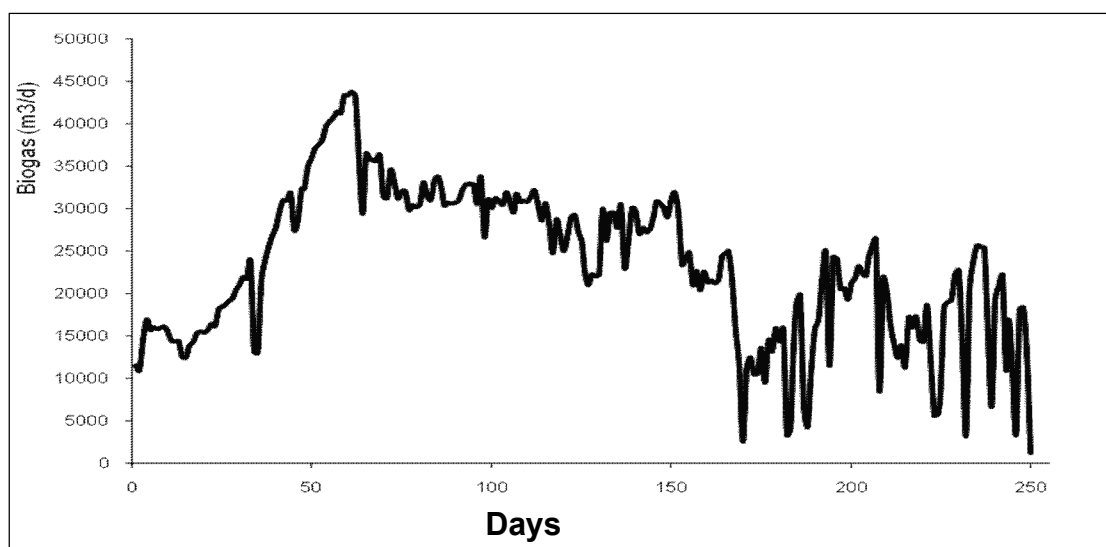


Fig. 6 : Variation in Biogas production rate.

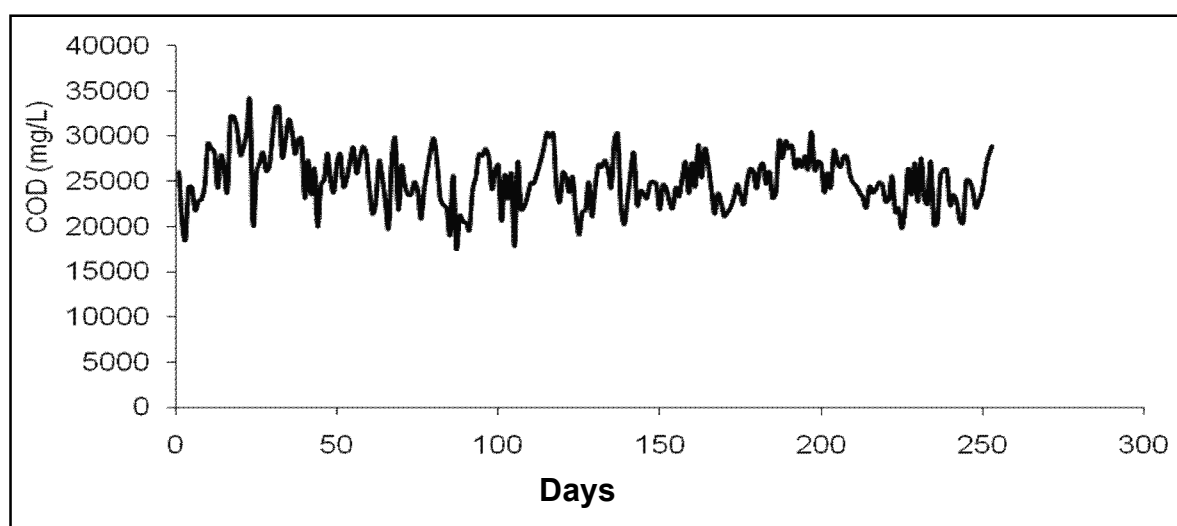


Fig. 7 : Variation in effluent COD.

the study period is shown in Fig. 2 to Fig. 7.

### Fuzzy model

The input and output parameters required to develop the fuzzy model are selected from the routine parameters used for daily monitoring and controlling the operation of the UASB reactor.

### Selection of Input parameters

The characterization of the UASB reactor was carried out by daily measurement of spent wash

flow rate, pH, temperature and COD at the inlet and measurement of effluent COD, VFA, pH, alkalinity and biogas production rate at the outlet. From these parameters other parameters like total COD reduction (tCODr), total COD loading (tCODl), Organic Loading Rate (OLR) and Hydraulic Loading Rate (HLR) can be computed. The variations in the input parameters affect the working of the UASB reactors, which is reflected in the form of effluent COD and biogas production rate. Higher COD reduction, i.e., lower effluent COD and maximum biogas production rate indicates proper working of the process.

As the pH and temperature are equalized in buffer tank due to recirculation of treated effluent, there is not significant variation in temperature, therefore it is not considered for the model development. Various combinations of input parameters were tried for development of fuzzy model to predict the biogas production rate. Optimum performance was obtained with the input parameters of total COD reduction observed before one day and two day (tCODr1, tCODr2), Biogas production rate on previous day (Biogas1), total COD loading (tCODl), pH<sub>eq</sub>, pH<sub>ef</sub> for current day for prediction of Biogas production rate (Biogas) on the same day. After inclusion of tCODr1 and tCODr2 i.e., total COD reduction observed on one day and

two days before improved the prediction of biogas production rate. The parameters tCODr1, tCODr2 and Biogas1 provided the back history of the reactor.

#### Fuzzification of input parameters

All parameter except pH are fuzzified in five fuzzy subsets and designated by linguistic variables; very low (VL), low (L), medium (M), high (H) and very high (VH). Three subset as Low (L), Medium (M) and High (H) are used for fuzzification of pH<sub>eq</sub> and pH<sub>ef</sub>. Combination of triangular and trapezoidal membership function is used for fuzzification of the input/output parameters. The triangular and trapezoidal membership functions are

$$\begin{aligned}\mu_A(x) &= 0, x \leq a; \\ &= \frac{(x-a)}{(b-a)}; a \leq x \leq b; \\ &= \frac{(c-x)}{(c-b)}; b \leq x \leq c; \\ &= 0; c \leq x\end{aligned}$$

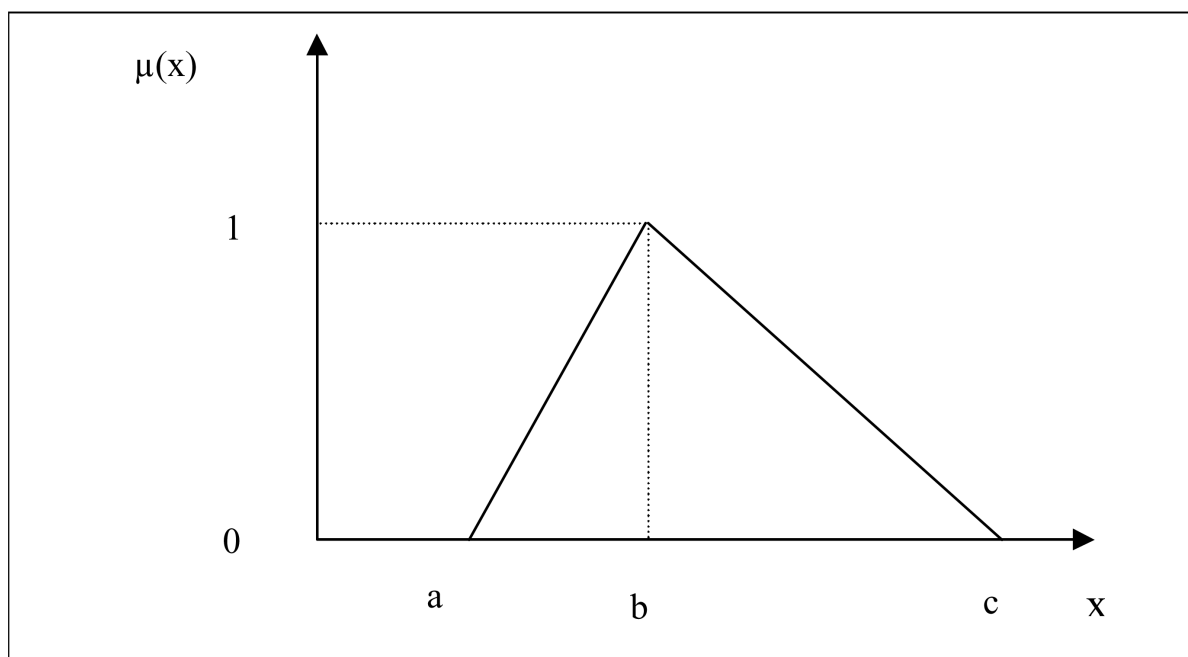
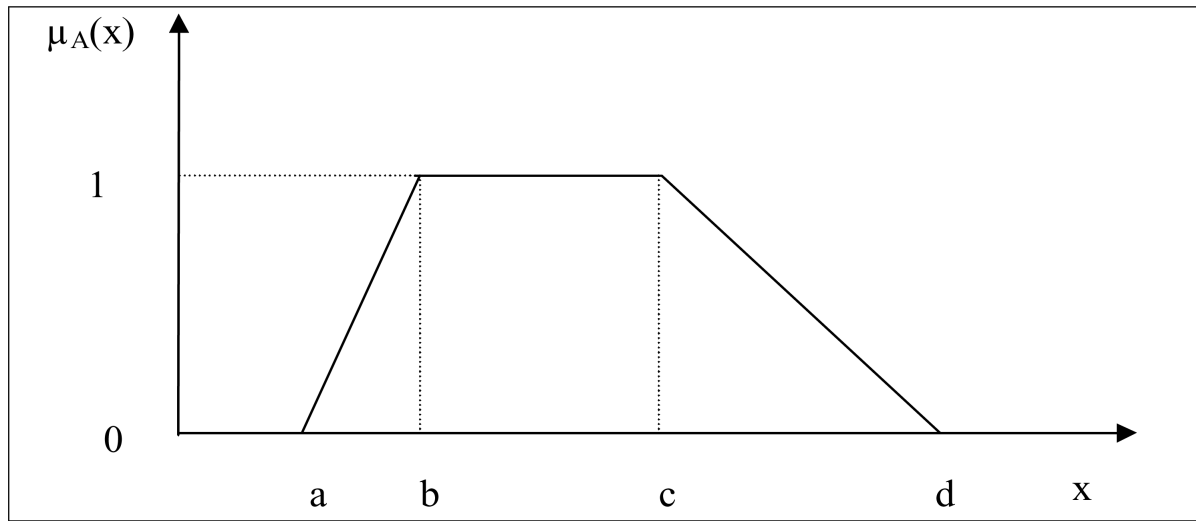


Fig. 8 : Triangular membership function.





**Fig. 9 :** Trapezoidal membership function

The trapezoidal membership function can be calculated by equations given below.

$$\mu_A(x) = 0; x \leq a$$

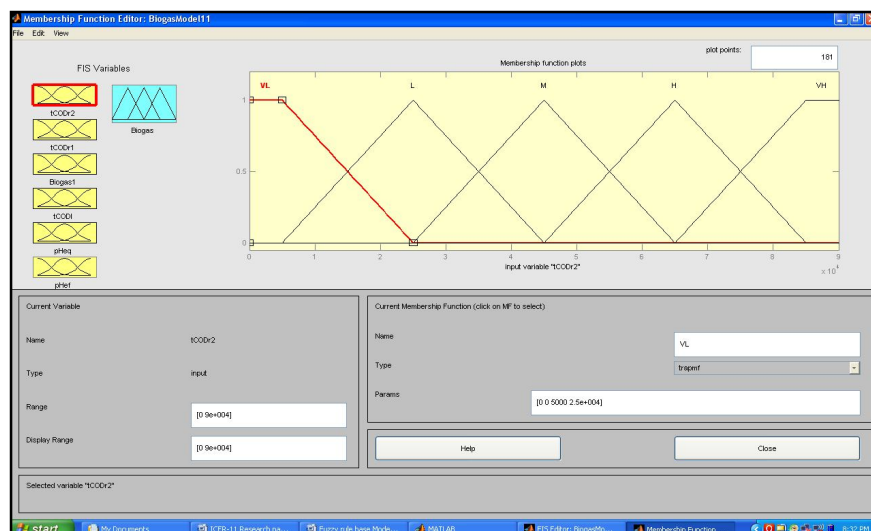
$$= \frac{(x-a)}{(b-a)}; a \leq x \leq b$$

$$= 1; b \leq x \leq c;$$

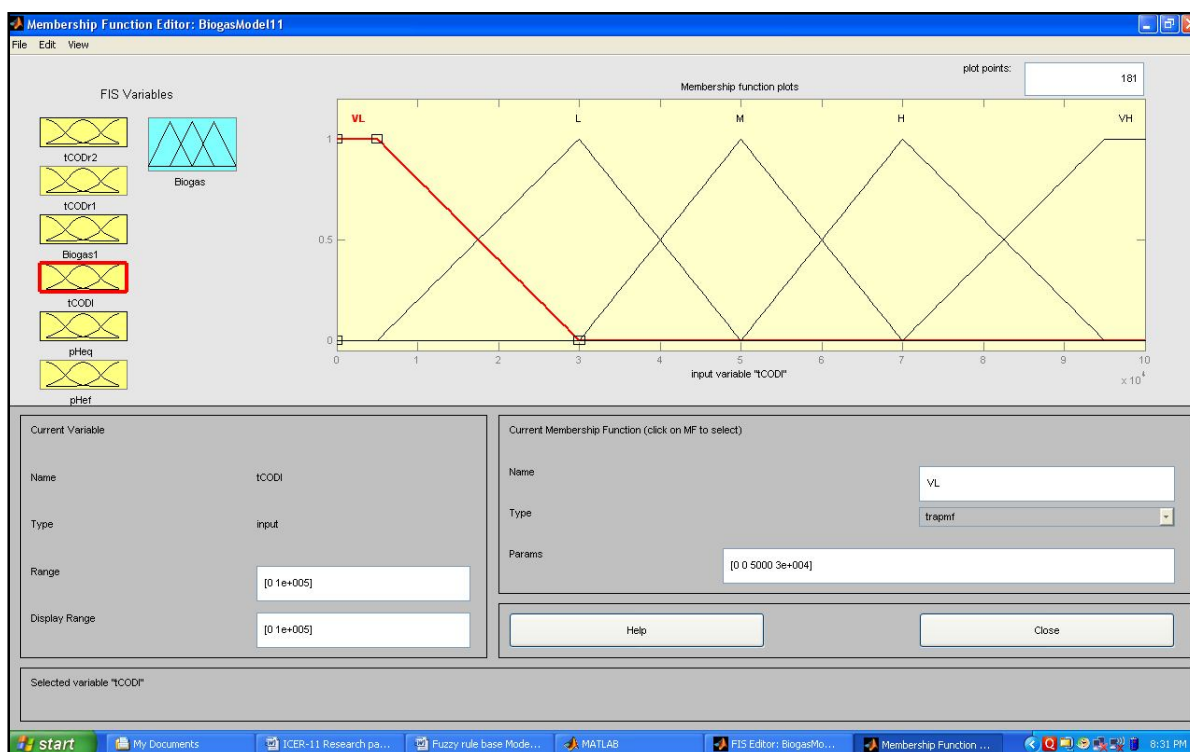
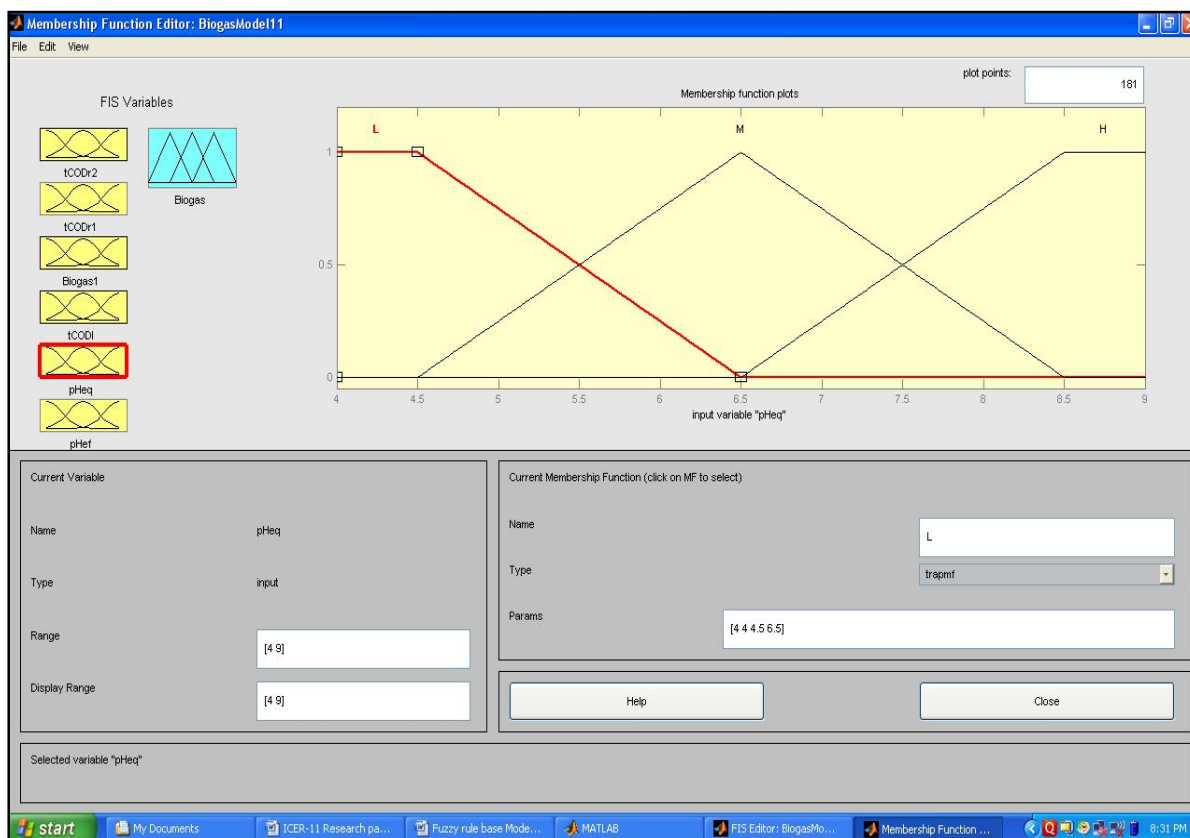
$$= \frac{(d-x)}{(d-c)}; c \leq x \leq d;$$

$$= 0; d \leq x$$

The range of each membership function for the input and output parameters is decided on the basis of domain of data, expert's knowledge and plant operator's opinion <sup>3,6,13</sup>. The membership functions for the input and output parameters are shown in **fig. 10** to **Fig. 13**.



**Fig 10 :** Membership function for total COD reduction (tCOD<sub>r,1</sub> and tCOD<sub>r,2</sub>).

Fig 11 : Membership function for total COD loading ( $tCOD_I$ ).Fig 12 : Membership function for equalized and effluent pH ( $pH_{eq}$  and  $pH_{ef}$ ).

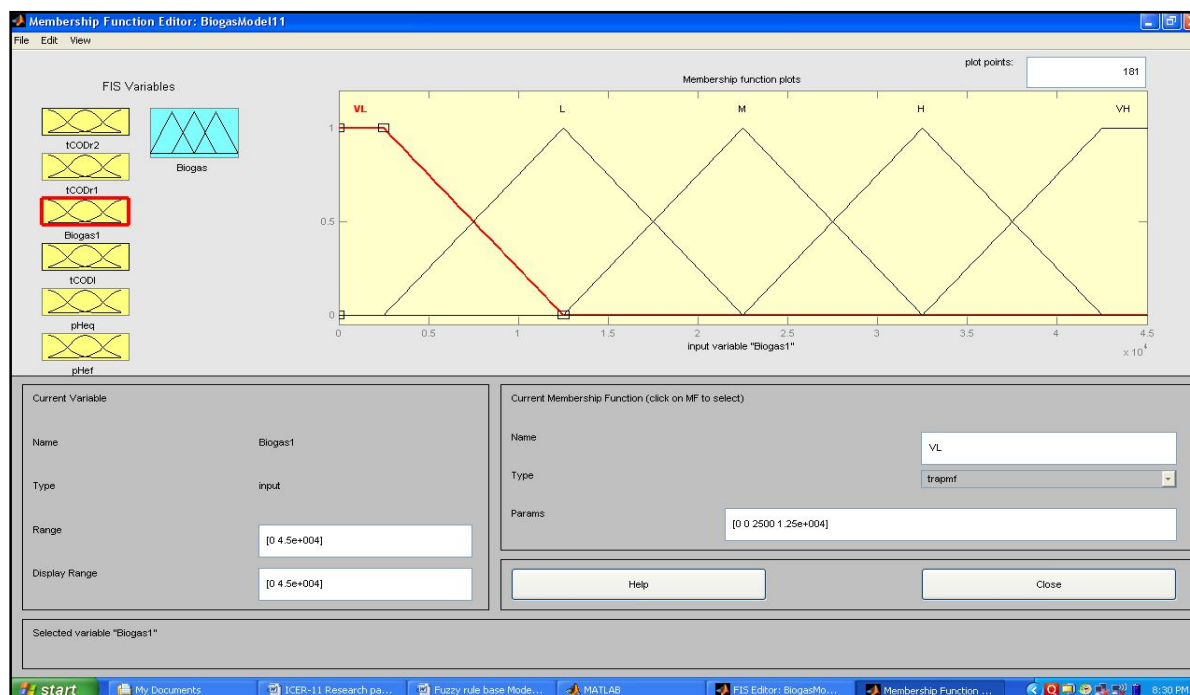


Fig 13 : Membership function for Biogas production rate (Biogas1 and Biogas)

defined as shown in **Fig. 8** and **Fig. 9**. The triangular membership function can be calculated by the equations given below.

### Structure of the Fuzzy Model

Fuzzy rule based models are used for nonlinear systems like biological wastewater treatment systems. Fuzzy models with different set of input and output parameters were studied for prediction of biogas production rate. The fuzzy model with input parameters as  $tCOD_r2$ ,  $tCOD_r1$ , Biogas1,  $tCOD_l$ ,  $pHeq$ , and  $pHef$  produced satisfactory prediction of Biogas production rate. The  $tCOD_r2$ ,  $tCOD_r1$  and Biogas1 indicate total COD reduction observed on two day and one day before the current loading whereas Biogas1 is the biogas production observed on one day before. The parameters total COD reduction ( $tCOD_r$ ) and total COD loading ( $tCOD_l$ ) are calculated as below,

$$1) tCOD_r = Q(COD_{in} - COD_{ef}),$$

$$2) tCOD_l = Q(COD_{in}),$$

where,  $Q$  = Spent wash flow rate ( $m^3/d$ ),

$COD_{in}$  = COD ( $Kg/m^3$ ) of raw spent wash applied to the reactor,

$COD_{ef}$  = COD ( $Kg/m^3$ ) of treated spent wash,  
 $tCOD_r$  = total COD reduction observed in the reactor in  $Kg/d$  and

$tCOD_l$  = total COD loading in  $Kg/d$  applied to the reactor.

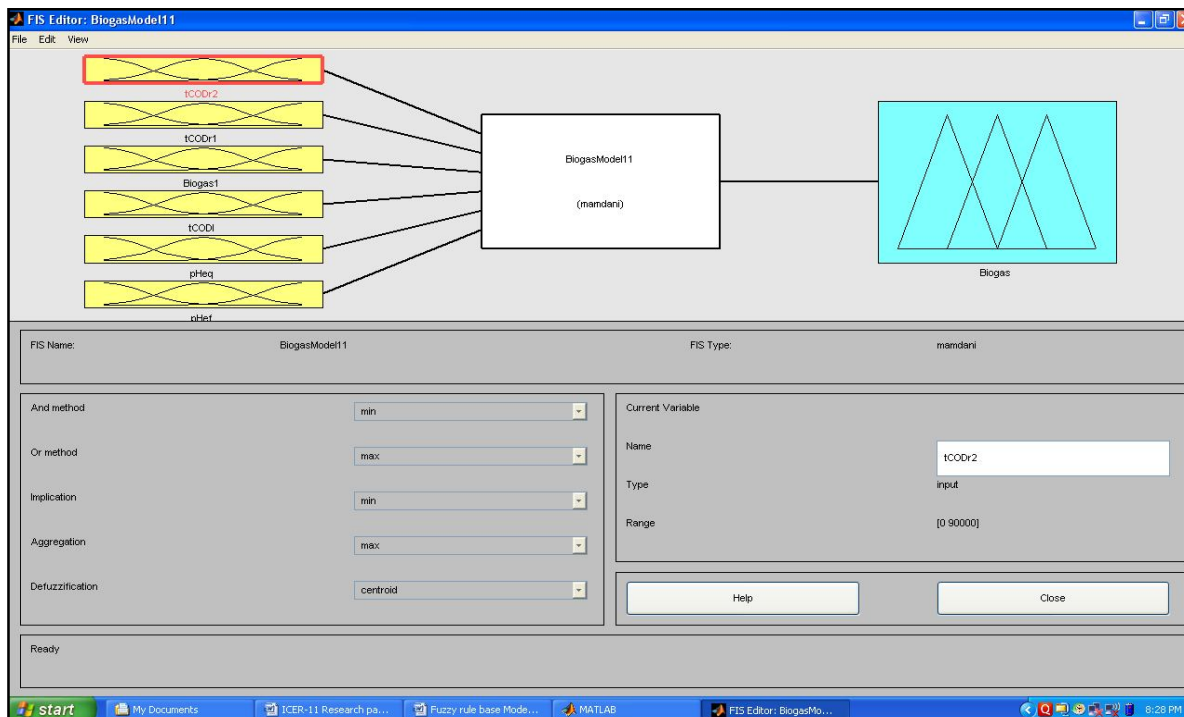
Fuzzy logic tool box of MATLAB version 7 with Mamdani's model was used for designing rule base. The fuzzy logic toolbox provides ready to use fuzzy inference systems. The predictive performance of the model depends on the number of fuzzy rules, number and type of membership function. The maximum number of fuzzy rules theoretically required to describe a biological process are  $n^x$ , where 'n' is number of membership function in each variable and 'x' is the number of variables in the system, which is very large and practically unmanageable. However less than 50 rules are necessary for acceptable control of a biological wastewater treatment process<sup>6</sup>.

Fuzzy rule base consisting of IF THEN rules was designed considering expert knowledge, opinion of plant operator and the trend of the data. The data was collected for about 310 days. Part of the data was used for model development and remaining for model validation. The optimum number of fuzzy rules was obtained by trial and

error. The structure of the model is shown in **fig. 14**. Optimum performance in prediction of biogas production rate for the model was obtained with 60 IF THEN rules. The nature of fuzzy rule base used in the model is given below. If tCOD<sub>r</sub>2 is *Medium* AND tCOD<sub>r</sub>1 is *High* AND

Biogas1 is *Medium* AND tCOD<sub>i</sub> is *Medium* AND pH<sub>eq</sub> is *Low* AND pH<sub>ef</sub> is *Medium* THEN Biogas<sub>rate</sub> is *Medium*.

The fuzzy toolbox uses MIN operator (AND method) for inference of a fuzzy rule. The final output of all rules is a fuzzy set obtained by



**Fig 14 :** Structure of the fuzzy rule based model.

MAX operator. The centroidal method is used

$$x^* = \frac{\sum_{i=1}^n x_i \mu(x_i)}{\sum_{i=1}^n \mu(x_i)}$$

for obtaining crisp output of the model for given set of input parameters. Following equation is used for defuzzification of the fuzzy set obtained by inference of various rule.

#### Testing of the Fuzzy Model

Separate data set was collected for 150 days on differed time period for model validation. The output of the model is a fuzzy subset which is defuzzified to crisp value in m<sup>3</sup>/d. **Fig. 15** shows the plot between the actual values and predicted values of biogas production rate. The performance of the model was evaluated using

statistical parameters. The correlation coefficient R of 0.9039 and root mean square error (RMSE) of 3250.59 was obtained between observed and predicted values of biogas production rate. The R value of 0.8 and above is considered to be satisfactory<sup>11</sup>. The RMSE values appears to be higher, however the maximum value of biogas production rate for the UASB reactor is 43500 m<sup>3</sup>/d and the RMSE value is 7.47% of maximum value. For a real scale UASB reactor, variation less than 10 % in prediction of biogas production can be considered satisfactory. R value of 0.9039 and RMSE of 3250.59 indicates good agreement of the predicted values with the observed values. It is observed that prediction of the biogas production rate for an UASB reactor treating distillery spent wash is influenced by the input parameters of Spent wash flow rate, influent COD

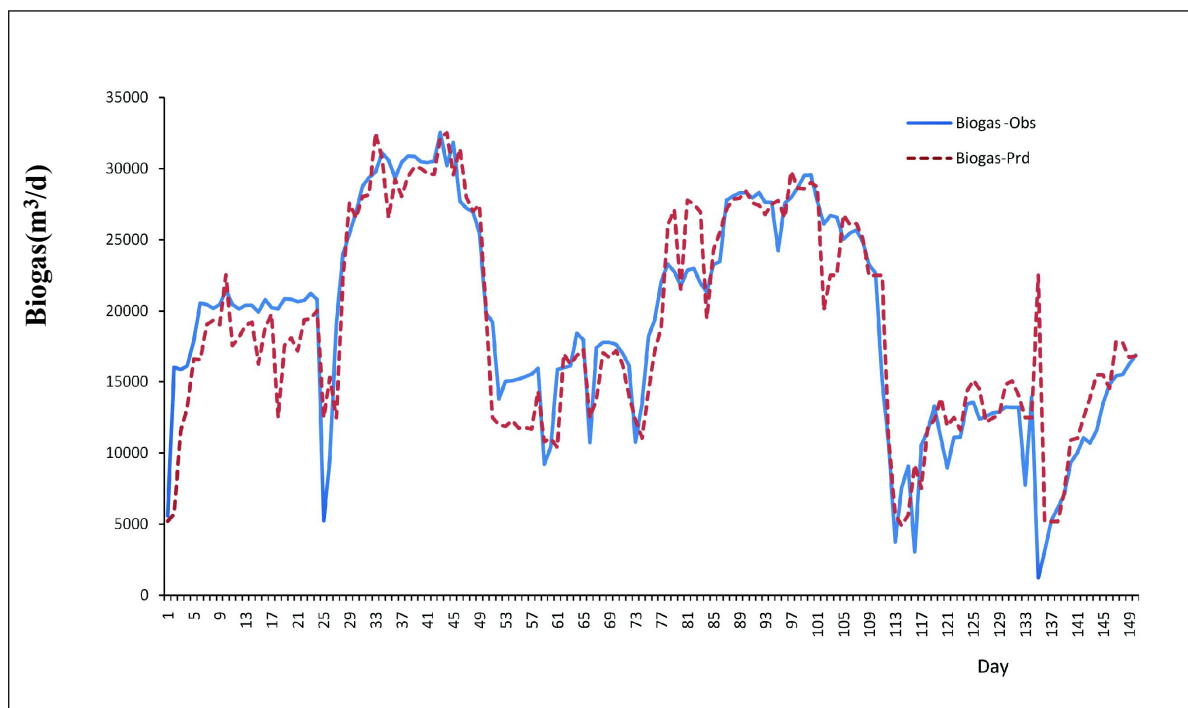


Fig. 15 : Time series plot between observed and predicted values of Biogas production rate.

(COD<sub>in</sub>), effluent COD (COD<sub>ef</sub>) on one day and two days before and Biogas production observed on one day before, i.e. (tCOD<sub>r2</sub>, tCOD<sub>r1</sub>, Biogas<sub>1</sub>, tCOD<sub>1</sub> and pH of equalized flow and treated effluent).

## CONCLUSION

The fuzzy model gives satisfactory prediction of biogas production rate for a real scale UASB reactor treating distillery spent wash. The model is developed on the basis of some of the routine parameters such as spent wash flow rate, influent COD, effluent COD, pH<sub>eq</sub>, pH<sub>ef</sub> and biogas production rate used for operation and control of the reactor. As the variation of biogas production rate is unpredictable in nature under given set of input parameters, fuzzy logic approach is used to develop a model to define the relation between the input and output parameters. This model will be useful in the field to assess the performance of the UASB reactor under different loadings applied to the reactor. The output of the model for given set of input parameters will be useful for assessment of the performance of the real scale UASB reactor treating distillery spent

wash after tuning the model for the plant under consideration. Variation between actual biogas production rate and predicted biogas production rate will be useful to understand proper working of the plant and hence to control the operation of the UASB plant.

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