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Performance and Kinetics of a Huasb Reactor for Treating Tapioca-Based Starch Industrial Waste Stream

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***Abstract*— In this paper, performance of a HUASB reactor for treating a tapioca-based starch industrial waste stream has been studied under six influent COD concentrations (ranging from about 1700-5800 mg/l) and five hydraulic retention times (HRTs) (ranging from 8 to 24 hours). The performance of HUASB reactor was evaluated based on COD removal (%) and bio-gas yield. Salient kinetic co-efficient of the HUASB reactor were determined by a modified-Monod based model and the dominant species in the sludge granules of the reactor was also identified. From an overall assessment, the better performance of HUASB reactor over the UASB reactor, for treating the above waste stream has been highlighted.**

Keywords: HUASB and UASB reactors; Tapioca-based starch industrial waste stream; COD removal (%); Bio-gas yield; kinetic co-efficients and Performance evaluation.

I. INTRODUCTION

In recent years, HUASB (Hybrid Upflow Anaerobic Sludge Blanket) reactors are used for treating a variety of waste streams, than UASB reactors, due to proven advantages of the former over the latter. However, critical review of literature on HUASB and UASB reactors for treating a variety of effluents, have revealed that studies on HUASB is rather few, when compared to reported studies on UASB and Hybrid Anaerobic Reactors (HAR). Further reported studies on starch-based waste stream (like cassava, tapioca) using HUASB reactor are rather rare [Govindaradjane, 2006]. Hence, there is a necessity and also there exists ample scope for investigating tapioca-based starch effluent under identical laboratory conditions and evaluating the performance of UASB and HUASB reactors. In this paper the performance of a HUASB reactor has been evaluated based on pre-set parameters, for treating a tapioca-based starch industrial waste stream and compared with that of a UASB reactor under identical conditions of operations to highlight the better performance of the HUASB reactor.

II. MATERIALS USED

A. Effluent: Source, Sampling and Characteristics

The effluent was collected from a starch industry located near Pondicherry, South India, and stored at 4°C under controlled conditions. The frequency of collection of effluent was once in three months so as to determine variations, if any, in the characteristics of the effluent over a period of 12 months.

The salient physico-chemical characteristics of the starch effluent samples were determined based on standard methods for examination of water and waste water, 21th edition (APHA, 2005) and are given in Table 1. The effluent is found to be acidic and found to have a very high initial concentration of COD. Based on BOD/ COD ratio of 0.61, it is assessed that the chosen effluent is amenable for anaerobic digestion.

B. Support Media

In the case of anaerobic reactors, support media made from synthetic material, especially using polymers have been used predominately. For example, plastic pall rings, polyurethane rings, polypropylene pall rings, polyethylene cascade rings, nylon fibres have been used. Natural materials (including materials) like blast furnace slag, volcanic rocks, ceramic rasching rings have also been used, but scarcely. In the present study, commercially available PVC based support media comprising of numerous windings (or) S-shaped portions, was used. The specific surface area of the above media is ten times more than the conventional media. Salient characteristics of the chosen support media (as furnished by the manufacturer), is given in Table 2.

III. EXPERIMENTAL INVESTIGATION

A. Experimental Set-up

The experimental set-up (for continuous mode of operation) consisted of UASB and HUASB reactors, made of perspex (acrylic) material with a cylindrical column of 100 mm internal diameter; 1600 mm height; total volume of 11.0 litres; effective volume of 9.7 litres and a gas liquid solid separator (GLSS) installed at the top of the reactor. The selected support media was located at the top one-third of the reactor, i.e., for 30 cm height. But for the support media, all other dimensions in HUASB reactor and UASB reactor are identical. The reactors were fed from the influent tank through silicon tube by means of a peristaltic pump of (Make : Miclin; Model : PP.20). A distributor was attached to the inlet pipe so as to facilitate uniform influent distribution. A space of 2.5 cms height was left between the distributor and the reactor base. The influent to the reactor is through its bottom and the reactants move from the bottom to the gas liquid solid separator (GLSS) at the top, where the gas gets separated and collected, which is measured by a wet gas meter assembly (working on the principle of water displacement).

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A brass check valve of 25 mm size was fixed at the bottom of the reactor to facilitate the sludge withdrawal. Five sampling ports were installed along the height of the reactor at different zones viz., sludge bed zone, sludge blanket zone and settling zone. The influent tank was provided with an agitator to ensure proper mixing of waste water. The treated effluent from the top of reactor is obtained by overflow through the GLSS at the top of the reactor. In the head space, an outlet for flow of gas was provided at the top most conical part of the reactor. This outlet was connected through a silicon tube to a wet gas meter. A photograph of the experimental set-up is shown in Fig.1.

B. Acclimatization and Start-up

The batch process was carried out in a batch reactor and the reactor was inoculated with active biomass obtained from an anaerobic digester, which is in operation in the existing treatment facilities located at the same industry from which the effluent samples were collected. Small quantities of digested sewage (obtained from a local municipal sewage farm) and phosphate buffer were also added to the starch effluent. The starch waste water was amended with calculated quantities of nitrogen and phosphorus (buffer), maintaining the ratio of COD: Nitrogen: Phosphorus (COD: N: P) at 100: 5: 1. The values of COD and biogas production were monitored every 4 days and the monitoring was continued till the attainment of steady state, indicated by concordant values of COD and biogas production. It was found that the acclimatization of tapioca-based starch effluent in anaerobic batch reactor was completed in 65 days. The UASB and HUASB reactors (for continuous mode of operation) were seeded from acclimatized seed sludge got from the batch-mode operation to about 30-50% of the reactor volume initially, having VSS concentration of about 15,000 mg/l, considering the entire site of reactor. The raw waste water was diluted to a COD concentration having an average value of 1500 mg/l and the influent rate was limited to 0.0097 m^3/day (i.e., VLR of 1.50 kg.COD/m^3.day at a HRT of 24 hrs). The reactors were then operated continuously for 90 days under identical conditions and the effluent characteristics were monitored frequently at about 4-7 days interval, until the attainment of steady state. Further, the OLR adopted in this study and the monitoring frequency adopted were the same as the suggestions of earlier investigators [Lettinga (1991); Jayantha and Ramanujam (1995); Shivayoginath and Ramanujam (1999), Hampannavar (2010), Selvamurugan (2011), Aspasia et.al, (2012), Balasubramanian et.al, (2012)].

It was found that the start-up process of the reactors have been completed at the end of 90^{th} day and that the steady state condition has been obtained on the 68^{th} day and 82^{nd} day for the HUASB and UASB reactors, respectively. The maximum COD removal was 84.35% and 78.50% at an influent concentration of 1500 mg/l (at HRT 24 hrs) and the biogas yield 0.31 and 0.30 m^3/ kg.COD removal, for the above reactors.

C. Continuous Mode of Operation

After the attainment of steady state, the experiment was continued with two different combinations of operating parameters namely: (1) influent COD concentration (six concentrations, namely, 1746.70; 2488.60; 3493.30; 4548.10; 5229.75 and 5862.00 mg/l) and (2) rate of flow (five flow rates, namely, 404, 540, 606, 808 and 1212.50 ml/hr. which corresponds to 24,18,16,12 and 8 hours of hydraulic retention time - HRT). For each influent COD concentration, the experiments were carried out for five HRTs. Thus there were 30 combinations for the entire experimental work, for each type of reactor. During the entire experimental investigations, the VLRs and OLRs were in the range of 1.76 to 17.62 kg.COD/m^3.day and 0.088 to 0.635 kg.COD/ kg.VSS.day for UASB reactor; 0.076 to 0.629 kg.COD/ kg.VSS.day for HUASB reactor. VLRs were maintained the same for both the reactors.

For each combination of experimental work, various effluent parameters, namely, pH, alkalinity, VFA, VSS (in the sludge blanket and in the effluent), biochemical oxygen demand (BOD), chemical oxygen demand (COD), were determined during the entire experimental investigations, based on standard methods (APHA, 2005). The gas produced was measured using the wet gas flowmeter and recorded on the basis of COD removed (i.e., m^3/kg.COD removal). The composition of the gas collected from the reactors was analyzed for its composition using a gas chromatograph (G.C. – Shimadzu – 14A model, Japan).

D. Microscopic Examination of Granules

With a view to understand the morphology and the nature of different microbial species available in the sludge blanket of the reactors, scanning electron microscope (SEM) was used to obtain micrographs. The collected sludge samples were first fixed by soaking in phosphate buffered 6% glutaraldehyde aqueous solution for 1 hour, at less than 20° C, washed with phosphate buffer and then dehydrated with acetone and dried at room temperature. After transformation of samples on wet plate, it was sputter coated with platinum using a high vacuum evaporator. The samples were then observed under various magnifications in a SEM and relevant photographs were taken. The make and model of the scanning electron microscope used was JEOL JSM-5610 series, Japan. Based on the above, the surface characteristics of the granules and the dominant species present in the granules were identified.

IV. KINETICS OF HUASB REACTOR

A. Model Selected

Several investigators have proposed kinetic models for the anaerobic digestion process. An overview of the popular models is given in Table 3. According to Heertjes and Van Der Meer (1978), the UASB reactor has two distinct characteristics. The sludge bed and blanket could be described as a combination of completely mixed region and well mixed region, while the flow characteristics in the settling zone could be described as a plug flow (i.e., the content of waste water follows the principle 'first-in-first-out' and that longitudinal mixing is assumed to be almost negligible). However, rising gas bubbles from the sludge bed and blanket also provide mixing of the settling zone and hence, the flow regime in the settling zone cannot be considered as a perfect plug flow.

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Table 3: Overview of Kinetic Models for anaerobic digestion process

Sl. No.	Name of Model	Proposer/ Investigator(s)
1	Monod model	Monod (1949) Laurence and McCarty (1970) Chin (1981)
2	First order model	Pfeffer (1974)
3	Chen-Hashimoto model	Chen and Hashimoto (1978)
4	Diffusion model	Suidan et,al. (1987)
5	Singh model	Singh et,al. (1963)
6	Modified Monod model	Roels (1983)
7	Step-diffusion model	Lau-Wong (1985) Cecchi et,al. (1990, 1991)
8	Modified first order model	Converti et,al. (1997)
9	Inert nuclei model	Lettinga et,al. (1980)
10	Selection pressure model	Hulshoff Pol et,al. (1988)
11	Surface tension model	Rouhet and Mozes (1990)
12	Syntropic micro colony model	Fang (2000)
13	Heetjes and Van der Meer model	Heertjes and Van der Meer (1978)

But, Hwang and Hansen (1992) assumed the UASB reactor as a completely mixed, rather than, a plug flow reactor, taking the whole reactor volume as a control volume. In this study, the above approach was adopted and hence the kinetic model and equations described by them was assumed to be valid for determining the bio-kinetic coefficients of HUASB reactor. Therefore, from among the several models as outlined in Table 3, Heertjes and Van Der Meer model which is based on Monod-type kinetic model is assessed to be more suitable to explain the biological processes in the reactor considered in this study. A brief theoretical background of the above kinetic model, based on the model development presented by Hwang et al. (1992), is described in the following section.

B. Theoretical Background

Substrate concentration surrounding micro-organisms is an important consideration for evaluating kinetic parameters based on Monod-type kinetic models. Several investigators have emphasized the importance of food-to-microorganism ratio (F/M) or the total organic loading rate to evaluate process performance as well as effluent substrate concentration [Cook and Kincannen (1971); Grady and Williams (1975); Suschkka (1980); Hung (1984); Kincannen and Stover (1984), Amal Al-Saadi (2012), Coskun et.al, (2012), John Leju et.al, (2012)]. Since anaerobic micro-organisms, especially methanogens, are very sensitive to their environment, it is more desirable to consider the amount of substrate per micro-organism per unit period than effluent concentration. The total OLR takes into account both the flow rate and the concentration of the waste and is then defined as:

$$L_X = \frac{S_i Q}{X_a V} = \frac{S_i}{X_a \tau} \qquad \ldots (1)$$

where,

L_x- Organic Loading Rate [mass substrate (COD)/ Mass Biomass (VSS)/ Time];

S_i - Influent substrate concentration [mass substrate (COD)/ volume];

X_a - Active biomass concentration in the reactor [mass biomass (VSS)/ volume];

Q - Influent flow rate (volume / time);

V - Reactor volume (volume);

τ - Hydraulic Retention time (time).

The relationship between the substrate utilization rate (R) and the organic loading L_x becomes : $R = \frac{K X_a L_X}{K_L + L_X} = qX_a$ …(2)

where,

R – Microbial substrate utilization rate [mass substrate (COD)/volume/ time];

k – Maximum specific substrate utilization rate [mass substrate(COD)/ mass biomass (VSS)/ time];

K_L – organic loading rate at R = k/2 [mass substrate (COD)/ mass biomass (VSS)/ Time];

q - Specific substrate utilization rate; [mass substrate (COD)/ mass biomass (VSS)/ time]

Most models are developed by writing material balances describing the mass rate of change in substrate and on biomass. The flow diagram of the reactor without recycle is shown in Fig 2, where : S_e – effluent substrate [mass substrate (COD/ volume)]; X_e – biomass concentration in the effluent [mass biomass (VSS)/ volume]. A mass balance on the substrate can be written around the entire system in Fig.2, which can be expressed as:

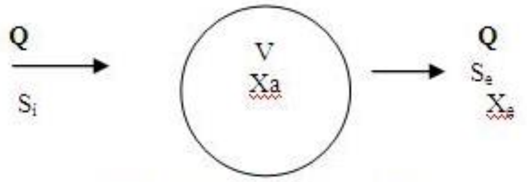

Fig: 2 Flow diagram of the reactor

$$\left(\frac{dS}{Dt}\right)_{net} V = QS_i - RV - QS_e \qquad \ldots (3)$$

where,

$\left(\frac{dS}{Dt}\right)_{net}$ - net change of substrate [mass substrate (COD)/ volume/ time]

At steady state, equation (3) can be combined with equation (2) as:

$$S_e = S_i - \frac{kS_i}{K_L + L_X} \qquad \ldots (4)$$

Similarly, a mass balance for the biomass gives:

$$\left(\frac{dX}{dt}\right)_{net} V = YRV - k_d X_d V - QX_e \qquad \ldots (5)$$

where,

$\left(\frac{dX}{dt}\right)_{net}$ - net change in rate of biomass [mass (VSS)/ volume/ time]

Y - Yield coefficient [mass of biomass produced (VSS)/ mass of substrate removed (COD)]

K_d - microbial decay coefficient (overtime)

At steady state, substituting equations (1) and (2) for substrate removal rate in equation (5) and solving for X_a:

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$$X_a = \left((S_i K Y - K_d S_i - K_L X_e) \pm \frac{\sqrt{(K_L X_e + K_d S_i - S_i K Y)^2 - 4 K_d K_L X_e S_i}}{2 K_d K_L \tau} \right) \quad \ldots(6)$$

Equations (4) and (6) have to be used to obtain the kinetic parameters k, K_L, K_d and Y. In this study, non-linear regression has been used to evaluate the above kinetic parameters. Equation (4) is used to evaluate k and K_L, whereas, equation (6) is used to evaluate K_d and Y. All other parameters in the above two equations are either known and computed and made available as input data. A standard (commercial) package (SPSS ver.11) was used for the above purpose. The computed values are used for evaluating the performance of the reactor.

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V. PERFORMANCE EVALUATION OF HUASB REACTOR

As one of the objectives of the study was to evaluate the performance of the reactor, COD removal (%) and biogas yield were chosen as significant parameters for the above evaluation. Apart from the above, salient kinetic coefficients of the reactor (biomass growth - Y, utilization rate – k), solids retention time (θ_c) and active bio-mass concentration (X_a) were considered for overall assessment of the performance of the HUASB reactor. Further salient results were compared with that of UASB reactor, obtained under identical conditions, to highlight the better performance of HUASB reactor.

A. *Status at Steady State Condition*

It is found that the start-up process of the reactor has been completed at the end of 90th day and the steady state condition obtained on the 68th day. The maximum COD removal is 84.35% at an influent concentration of 1500 mg/l (at HRT 24 hrs) and the biogas yield 0.31 m^3/ kg.COD removal. It can be seen that HUASB reactor has attained the steady state condition 14 days ahead of the UASB reactor and that the maximum COD removal is also higher under identical conditions and HRT [Govindaradjane (2006); Govindaradjane (2009)].

B. *Effect of OLR on COD Removal (%)*

At a particular HRT, as the OLR increases, COD removal (%) also increases and the above trend is found to be the same for all the influent concentrations. Similarly, as the HRT decreases, COD removal (%) also decreases and it is found to be independent of the influent concentrations considered (Fig.3). COD removal (%) and OLR values are found to be in the range of 83.10% to 72.10% and 0.076 to 0.629 (kg.COD/kg. VSS. day), considering the entire experimental values. Further, the maximum COD removal was 83.10 % which corresponds to the influent COD of 4548.10 mg/l (at 24 hrs. HRT). The above maximum COD removal is higher than (say about 78%) the reported values by various investigators for the treatment of starch-based waste streams by UASB reactors [Annachhatre and Amtya (2000); Karthikeyan and Sabarathinam (2002) and Govindaradjane (2006)].

C. *Effect of VLR and HRT on COD removal*

At a particular HRT (i.e. 24 hrs), as the VLR increases, COD removal (%) also increases (Fig.4). Maximum COD removal is 83.10 % corresponding to a VLR of 4.56 kg.COD/m^3.day. However, further increase in VLR (i.e., for 5.26 and 5.91 kg.COD/m^3.day) has led to reduction in COD removal (%). Further, as the HRT decreases (i.e. from 24 hrs to 8 hrs), VLR increases and the corresponding COD removal (%) decreases (Fig.5) and is independent of the influent concentrations considered and it is in agreement with the reported trends by Routh (2000) for various HRTs and with the reported results of Rajesh Banu and others (2006) at a constant HRT for treating a synthetic starch (sago) effluent using a HUASB reactor. The maximum COD removal efficiency (%) obtained in the HUASB reactor is comparable to the reported maximum COD removal efficiency by Fang and Kwong (1994), James and Kamaraj (2003), Balasubramanian et.al, (2012), for a starch waste stream and by Rajesh Banu and others (2006) for treating a synthetic starch (sago) wastewater.

D. *Gas Conversion*

In general, it is found that the biogas yield increases with COD removal efficiency (%) and OLR (Fig. 6 & 7). At a particular HRT, as the VLR increases, biogas yield also increases and as the HRT decreases, biogas yield also decreases for all influent COD concentrations. It is found that the biogas yield gradually increases initially with increase in COD removal (%), OLR, VLR and HRT (i.e., 0.27 m^3/kg.COD to 0.30 m^3/kg.COD removal) and thereafter the yield decreases with decrease in COD removal (%) (i.e., 0.28 m^3 to 0.24 m^3/kg.COD) (Figs.8 & 9). The salient composition of biogas collected from the reactor is given in Table 4. It is seen that the increase in methane content with increase in influent COD concentration is only marginal. However the actual methane content (%) in the HUASB reactor is marginally higher than UASB reactor, for treating identical (i.e., starch) waste stream.

E. *Effect of Biomass Concentration on COD Removal*

Biomass concentration has increased steadily from 23.21 to 32.06 g.VSS/l, with increase in VLR ranging between 1.76 to 5.91 kg.COD/m^3 (Fig.10). The maximum biomass concentration achieved in this reactor may be due to the support media provided at about one-third the height of the HUASB reactor.

F. *Variation of VSS in the effluent of HUASB Reactor*

VSS concentration of the effluent in the HUASB reactor shows an increasing trend with decreasing HRT and it was found to be in the range of 94.3 mg/l to 536.0 mg/l. VSS concentration of the effluent in the HUASB reactor was found to be less than the effluent concentration in the UASB reactor under identical conditions (Govindaradjane, 2006). This may be attributed to the presence of packed media which helps to develop attached growth and hence to retain the VSS in the reactor to some extent, when compared to UASB reactor.

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VI. MICROSCOPIC EXAMINATION OF GRANULES

Granular sludge mainly occurs in the lower regions of the reactor and forms a sludge bed with a solid content of about 25 g/l to 32 g/l in the reactor. The growth of propionate utilizing bacteria would be responsible for the increase in VSS content of granular sludge while acetoclastic microflora production will be less (Guiot et al., 1992). Further, the strength of granules shown to have a bearing on the operating conditions (Gangrekar et al., 1996). The granulation of seeded sludge is shown to be substrate dependent and it may not occur at all for same specific substrates. At the end of the operation, the granular sludge was sampled from the reactions to determine its characteristics sampled from the reactors to determine its characteristics.

Fig.11 shows the micrograph at 4500/ 8500 times of magnification of the sludge granules from HUASB reactor. It is observed that the overall surface of granules sludge are rough and uneven, and most granules appear to be compact with few cavities. Further it is observed that *Methanothrix*-like bacteria were found to be the dominant species in the granules.

It can be seen that the surface characteristics of the granules of the reactor and the dominant species of the granules determined in this study are similar to the reported results of Fang et.al.(1995); Yang and Anderson (1993); Jayantha & Ramanujam (1995); Sivayoginath & Ramanujam (1999) and Sumeeth Kumar (1998). Further no significant changes were observed between the granules obtained from UASB and HUASB reactors, considered in this study.

VII. KINETIC PARAMETERS OF HUASB REACTOR

Kinetic parameters, namely, k, K_L, k_d, Y, evaluated using equations 4 and 6 and are given in Table 5. It can be seen that all the parameters of HUASB reactor are very much lower than the corresponding parameters of the UASB reactor, evaluated under identical conditions. Kinetic parameters were also evaluated considering the results corresponding to each influent COD concentration, for both the reactors (Table 6). It can be seen that the kinetic parameters of UASB reactor exhibit a higher range than that of HUASB reactor.

VIII. REGRESSION RELANTIOSHIP FOR PERFORMANCE OF HUASB REACTOR

The performance of HUASB reactor was evaluated based on their capacities for removing COD. The HUASB treatment processes is dependent on Organic Loading Rate [kg.COD/ kg.VSS.day], Volumetric Organic Loading Rate [kg COD/m^3.day], Hydraulic Retention Time [days] and concentration of VSS in the sludge blanket [mg/l]. Typical regression relationships can be obtained considering the above parameters for evaluating the performance of the reactor, using the experimental data, which can be used later on to predict the performance of the reactors, for any other specified parameter.

In the present study, it is decided to use only a non-linear regression relationship, in view of its higher accuracy expected to model the relationship. Accordingly, a non-linear regression model is constructed using the above parameters which influence the substrate [COD] removal efficiency, with partial coefficients. A typical relationship is given in equation (7).

$$\text{COD removal efficiency (\%)} = A \pm a_1[OLR] + a_2[VLR] + a_3[HRT] + a_4[VSS] \quad \text{.... (7)}$$

The model was run for the corresponding observed experimental values obtained from the UASB and HUASB reactors, resulting in equations (8).

$$\text{COD removal efficiency (\%)} = 99.719 - 13.336[OLR] + 0.206[VLR] + 5.624[HRT] - 0.866[X_a] \quad (r^2 = 0.883, CI = 95\%) \quad \text{... (8)}$$

IX. CONCLUSION

Following are the salient conclusions:

(1) HUASB reactor has an early start-up (i.e., it attains the steady state condition 14 days ahead of UASB reactor), which is advantageous from the operation of the treatment process. It is also to be noted that the early start-up has not affected the performance of the reactor, especially, COD removal efficiency.

(2) The trend between OLR and COD removal (%) and between VLR and COD removal (%) are found to be same as that of UASB reactor , for the experimental ranges of HRTs and influent COD concentrations considered.

(3) However, the maximum COD removal is 83.10% at identical influent COD and HRT as that of UASB reactor, but at an OLR of 0.155 kg.COD/kg.VSS.day.

(4) The trend between bio-gas yield and COD removal (%) is found to be the same as that of UASB reactor, but, the maximum gas yield is slightly better and equal to 0.30 m^3/kg.COD removal, at identical HRT and VLR, but at an OLR of 0.155 kg.COD/kg.VSS.day. The methane content in the biogas generated in both the reactors are almost the same and is in the range of 54 – 56%

(5) From an overall assessment, it can be stated that the performance of the HUASB reactor is better than the UASB reactor and that the HUASB reactor contemplated in the present study is capable of handling still higher influent COD concentrations, than the experimental range of values of the present study. The better performance of HUASB reactor may also be attributed to the presence of support media provided at the top of the reactor which facilitate additional microbial growth.

(6) The overall surface of granules sludge are rough and uneven and that Methanothrix-like bacteria were found to be the dominant species in the granules.

(7) The system performance evaluated on the basis of various kinetic co-efficients is better in HUASB reactor than in UASB reactor and that the various co-efficients developed can be used for the design of reactors for sustaining the anaerobic treatment process.

(8) The non-linear regression relationship developed for the HUASB reactor can be used to predict the performance (in terms of COD removal efficiency) with higher degree of confidence.

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Table: 1 Characteristics of Tapioca-based Specialty Starch Effluent

Sl. No.	Parameters	Value / Description
1.	Colour	Very light brownish
2.	Odour	Alcoholic
3.	pH	5.69
4.	Alkalinity	2630
5.	Volatile Fatty Acids (VFA)	1625
6.	Total Suspended Solids (TSS)	720
7.	Total Dissolved Solids (TDS)	2200
8.	Total Volatile Solids (TVS)	1510
9.	Total fixed solids (TFS)	690
10.	Total solids (TS)	2920
11.	Biochemical Oxygen Demand (BOD)	3500
12.	Chemical Oxygen Demand (COD)	5750
13.	Total Khejdhal Nitrogen (TKN)	280
14.	Phosphorous (P)	25 – 48

Note : (i) All values except pH, are in mg/l
(ii) All values are average of four samples characterized over the period of investigation.

Table: 2 Characteristics of support media

Size Mm	Surface Area m^2/m^3	Void ratio %	Density gm/l
26	500	87	140
55	350	92	110

Table: 4 Salient Composition of biogas produced in the reactors

Sl No	Influent COD concentration mg/l	Methane content		Carbon di - oxide	
		UASBR	HUASBR	UASBR	HUASBR
1	1768.60	54.8%	57.9%	35.0%	32.0%
2	4563.20	56.1%	59.4%	32.0%	30.0%

Note: (i) the above influent concentrations were at HRT of 24 hrs.
(ii) Values of other gases, etc. are not indicated.

Table: 5 Kinetic Parameters of UASB and HUASB Reactors

Sl. No	Reactor Type	Kinetic Parameters			
		K	k_L	Y	k_d
1	UASB	1.086	1.329	0.087	0.021
2	HUASB	0.769	0.744	0.046	0.012

Note: The values are obtained considering the entire experimental results.

Table: 6 Comparisons of Kinetic Parameters of UASB and HUASB Reactors

Kinetic Parameters	UASBR	HUASBR
k [kg COD removed/ kg.VSS.day]	0.329<k<1.386	0.7869<k<0.989
k_L [kg COD/ kg.VSS.day]	$0.346<k_L<1.799$	$0.767<k_L<1.109$

K_d [per day]	$0.0136< K_d<0.0282$	$0.012< K_d<0.015$
Y [kg.VSS/kg COD]	$0.086<Y<0.115$	$0.0417<Y<0.1018$

Fig: 1 Experimental view of UASB and HUASB Reactors

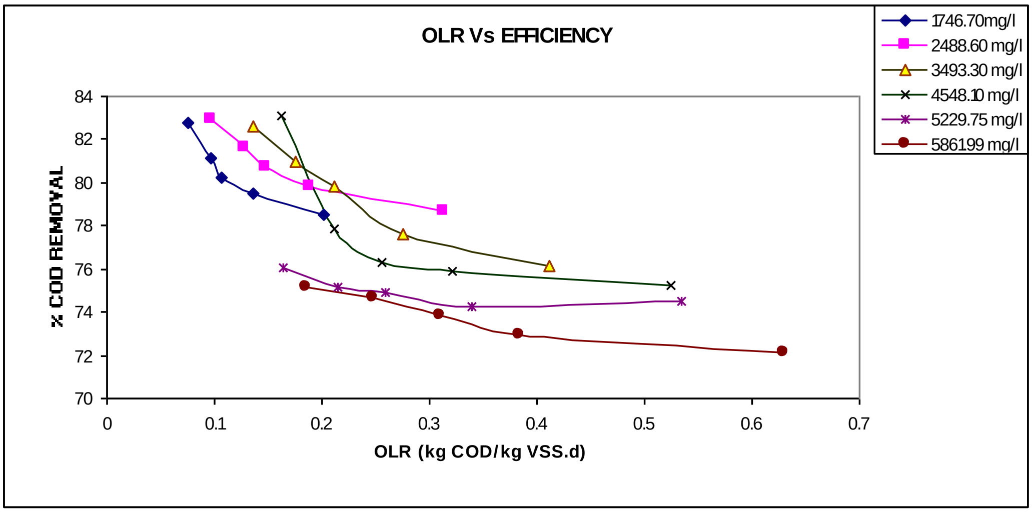

Fig. 3 OLR Vs COD removal (%) for various influent COD concentrations and HRTs for HUASB reactor

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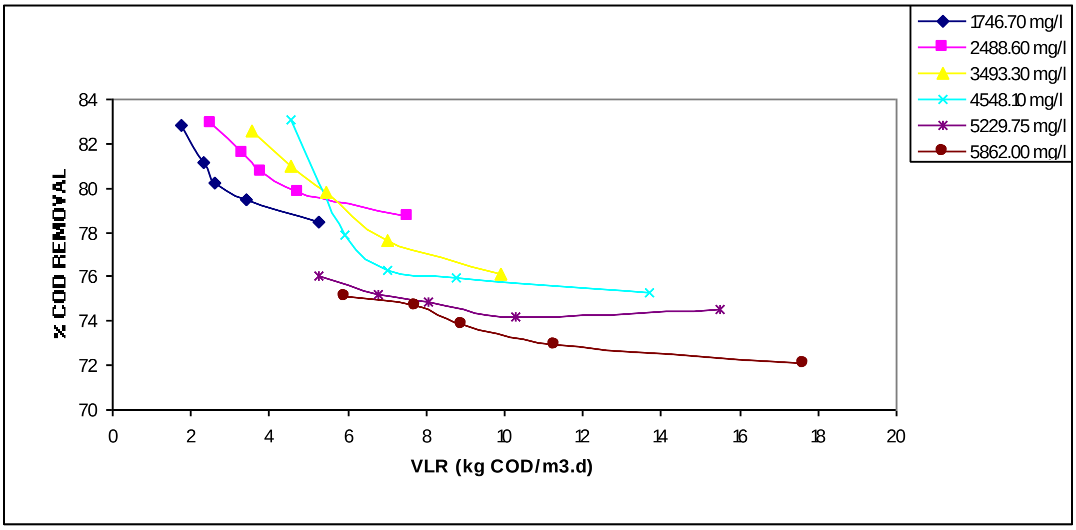

Fig. 4 VLR Vs COD removal (%) for various influent COD concentrations and HRTs for HUASB reactor

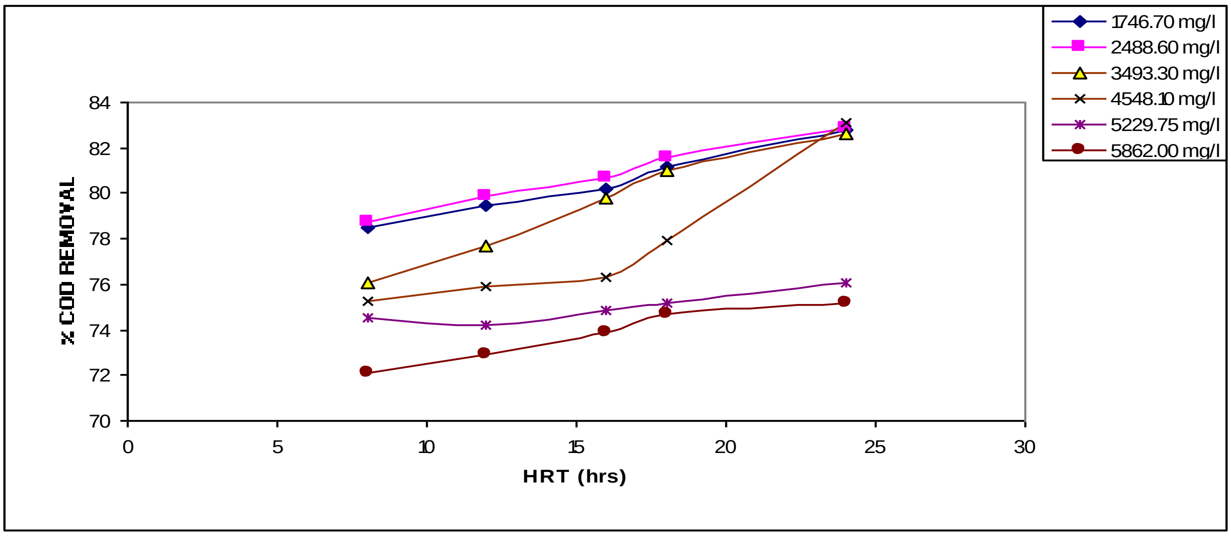

Fig. 5 HRT Vs COD removal (%) for various influent COD concentrations and HRTs for HUASB reactor

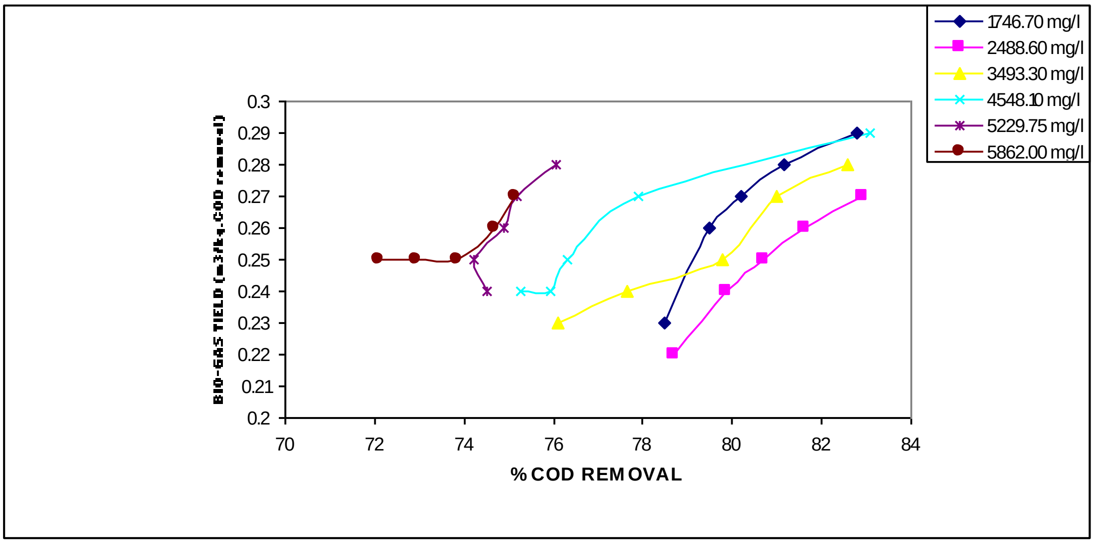

Fig. 6 COD removal (%) Vs Bio-gas yield for various influent COD Concentrations and HRTs for HUASB reactor

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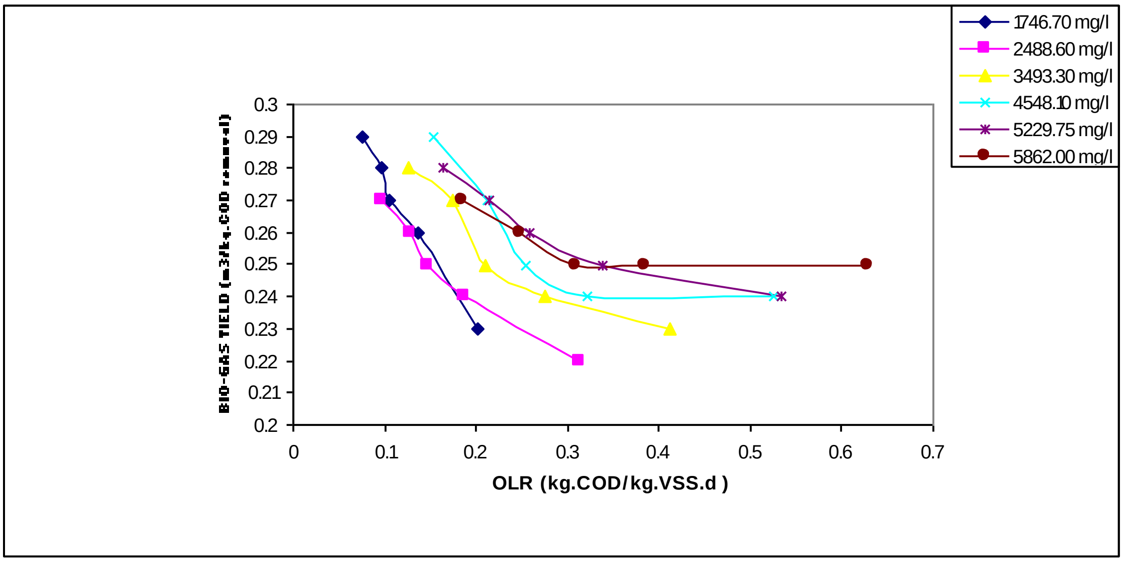

Fig. 7 OLR Vs Bio-gas yield for various influent COD Concentrations and HRTs for HUASB reactor

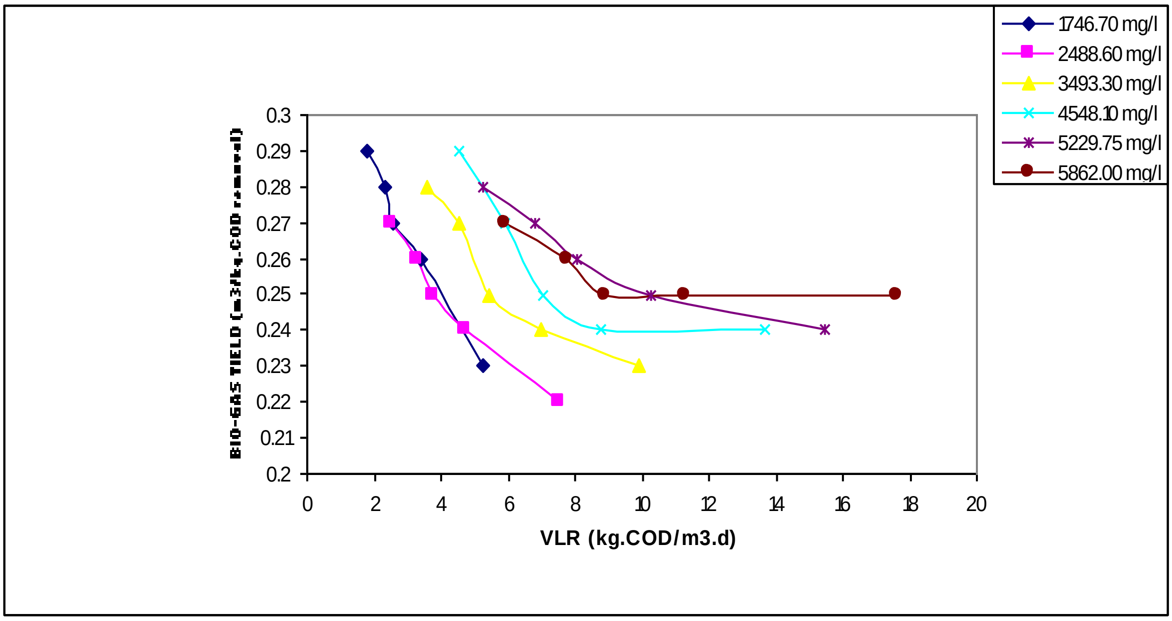

Fig: 8 VLR Vs Bio-gas yields for various influent COD Concentrations and HRTs for HUASB reactor

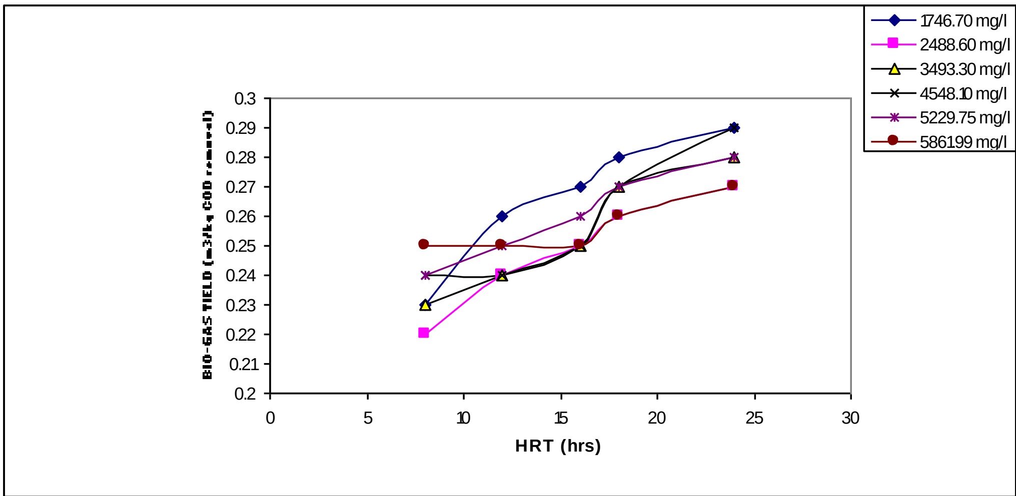

Fig: 9 HRT Vs Bio-gas yield for various influent COD Concentrations and HRTs fo HUASB reactor

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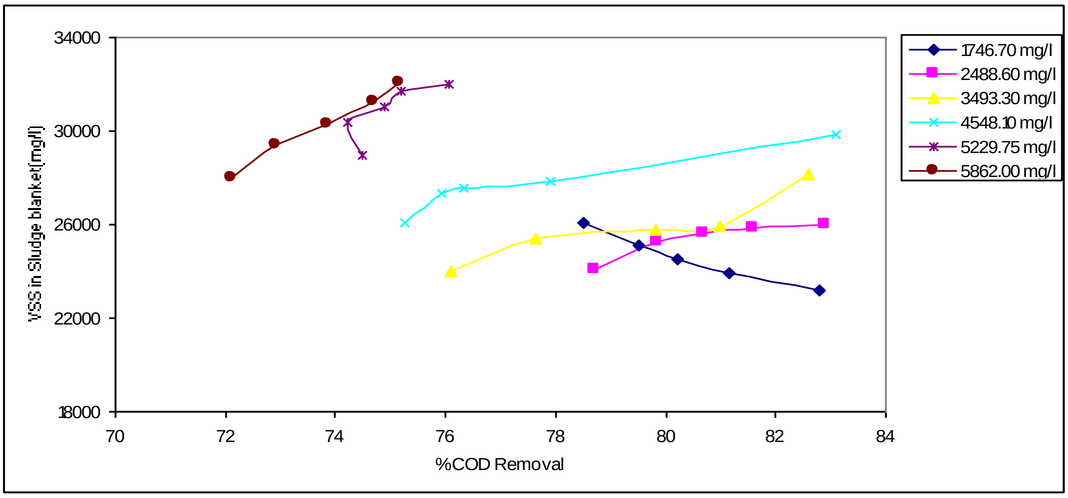

Fig: 10 COD removal (%) Vs VSS for various influent COD Concentrations and HRTs for HUASB reactor

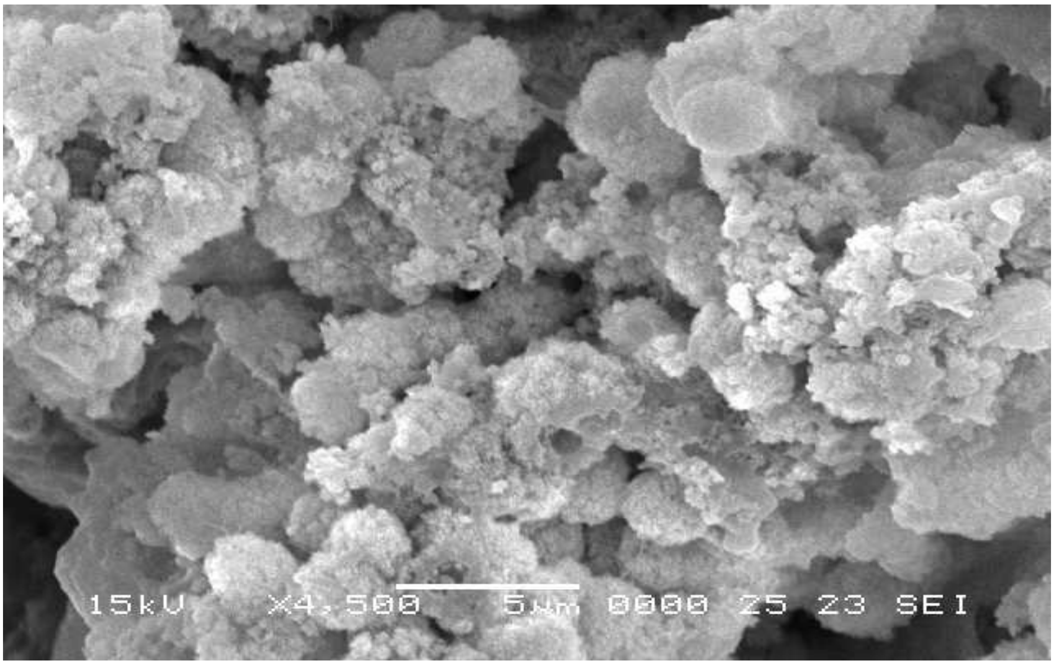

Fig: 11 SEM photograph surface view of granules from HUASB Reactor.

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