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EFFECT OF OPERATIONAL AND DESIGN PARAMETERS ON REMOVAL EFFICIENCY OF A PILOT-SCALE UASB REACTOR TREATING DAIRY WASTEWATER

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ABSTRACT

A pilot scale study was conducted on the mesophilic (20 - 42°C) anaerobic digestion of dairy wastewater by UASB reactor, operated on anaerobic sludge granules developed from digested cow dung slurry and earthworm cultured soil. The aim of this study was to explore the effect of operational and design parameters on removal efficiency of a pilot-scale UASB reactor treating dairy wastewater. A PVC pipe with a diameter of 150 mm and total height of 103.6 cm and effective height of 79.2 cm was used as a reactor. The digestion and a 3-phase separator element had a volume of 0.014 and 0.00431 m^3 respectively. The COD concentrations used in the present study ranges between 800 mg/L to 4080 mg/L while the BOD concentrations ranges between 384 mg/L to 1880 mg/L. The digester efficiency of treating dairy wastewater at various HRT of 6, 12, 24, 48 and 72 h and OLR corresponding to HRTs were 2.77, 2.16, 1.574, 1.052, 0.54 kg COD/m^{3}d and 1.276, 0.995, 0.741, 0.515, 0.261 kgBOD/m^{3}d respectively, at 0.0224 m/h upflow velocity was studied and its performance was assessed by monitoring pH, BOD5 and COD. During this study, which lasted for 44 days, no heat exchanger was used and pH was maintained between 7.1 to 7.7. Finally the COD concentrations of the UASB reactor effluent with optimum HRT of 48 h and OLR of 1.052 kg COD/m^{3}d was obtained 557 mg/L corresponding to treatment efficiency of 64%. While the BOD concentrations of the UASB reactor effluent with optimum HRT of 48 h and OLR of 0.515 kgBOD/m^{3}d were obtained 202.6 mg/L, corresponding to treatment efficiency of 73.3 %. At the end of experiment, a granular sludge with good settling properties was produced.

INTRODUCTION

Dairy industry has grown in most countries of the world because the demand for milk and milk products has steadily risen. Simultaneously, the production of milk per head of cattle has also grown as a result of advancements in veterinary science (Poompavai, 2002). The dairy industry produces different products such as pasteurized, condensed, skimmed and powdered milk, yoghurt, butter, different types of desserts and cheeses and sometimes cheese whey (Carozzi, 1993). Among nations, India is one of the largest, and is projected to become the largest producer of milk and dairy products in the

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world (Gupta, 1997). India is also by far the largest producer of dairy based wastewaters of the world as well. Dairy industries release large quantities of wastewater often in the order of thousand cubic meters/day (Wheatley, *et al.* 1991). It is estimated that dairy industry uses 2 to 5 L of water per L of milk processed (Amritkar, 1995). Most of the wastewater produced in the dairy industry results from cleaning of transport lines and equipment between production cycles, cleaning of tank trucks, washing of milk silos and equipment malfunctions or operational errors (Danalewich *et al.* 1998). These wastewaters are rich in biodegradable organics and nutrients (Poompavai, 2002; Ramasamy and Abbasi, 2000). The DWW is similar to most other agro-industries wastewaters, characterized by high BOD and COD concentrations representing their high organic content (Orhon, *et al.* 1993). The main contributors to the organic load of these wastewaters are lactose, fats and proteins (Hansen and Hwang, 1990; Perle *et al.* 1995). If not treated, High concentration of organic matter in dairy wastewater causes pollution problems to surroundings (Perle *et al.* 1995). But they also have the potential to supply carbon in a form that anaerobic microorganisms can convert into methane (Franklin, 2001).

This opens up the possibility of generating clean fuel (methane) with concomitant pollution control. Therefore, appropriate treatment is required prior to disposal into sewer network or receiving water bodies. Though DWW is generally characterized by its relatively high temperature and variation in organic content, so anaerobic treatment is considered the appropriate choice (Bangsbo-Hansen, 1985; Hammes, *et al.* 2000). Anaerobic method for the treatment of DWW is attracting the attention of researchers because of the presence of high organic content in the waste, low energy requirement of the process, lesser sludge production and generation of fuel in the form of methane (Ghaly and Pyke, 1991). In one such attempt the efficiency of UASB reactor (Datar *et al.* 2001) has been studied. Also the possibility of employing a high-rate anaerobic process based on UASB reactor to generate some energy in the form of methane-rich biogas has been explored and some energy saved because UASB reactors do not need aeration and churning (which aerobic activated sludge process does). The UASB reactor was introduced by Lettinga (Lettinga *et al.* 1980) and subsequently developed extensively by others (Lettinga and Pol, 1991; Kida *et al.* 1993; Frigon and Guiot, 1995; Sipma *et al.* 1999; Manjunath *et al.* 2000; Yu *et al.* 2001; Buzzini and Pires, 2002; Sponza, 2003 and Chang and Lin, 2004). UASB reactor hold particular attraction because it can handle higher suspended solid loads and shock loads, besides wastewaters of a greater range of strengths, than other type of reactors (Lettinga and Pol, 1992 and Xu *et al.* 2003).

The success of the UASB reactor is because of its high removal efficiency even at light loading rates and low temperature, low energy consumption, low sludge production, low space requirements and low nutrients compared to aerobic treatment (Lucas Seghezzo, *et al.* 1998; Güven, *et al.* 2009). Fig. 1, based on a number of papers published on the treatment of industrial wastewaters of different strengths by UASB during 1999-2010, indicates that UASB appears most well suited for high strength wastewaters e.g., DWW, followed by medium strength and only a small fraction of reports are on low strength industrial wastewaters. The presence of carbohydrates, as in DWW, promotes the production of extracellular polysaccharides, which enhance bacterial agglomeration and hence are believed to be essential to the formation of granules necessary for the success of UASB reactors (Quarmby and Forster, 1995; Batstone and Keller, 2001). Some additives have been shown to enhance sludge granulation, specially natural and cationic polymers (El-Mamouni *et al.* 1998) which may also be present in DWW. The most characteristic device of UASB reactor is the three phase separator or settler. The presence of the settler on the top of the digestion zone enables the system to maintain a large sludge mass in the UASB reactor, while effluent essentially free of suspended solids is discharged. In this paper, the feasibility of using UASB reactors for DWW treatment and energy recovery has been explored. An important aspect in this study is to assess the ability of the UASB to produce wastewater suitable for safe discharge into receiving water bodies and agricultural drain.

MATERIALS AND METHODS

Wastewater sampling and characterization

Table 1. Mean Characteristics of DWW

Parameters	Mean ± Standard deviation
pH	7.9 ± 1.6
BOD, mg/L	1342±538
Soluble Total	428±126
COD, mg/L	2820 ± 1260
Soluble Total	2185±1083
Total Solid, mg/L	3470 ± 90
Suspended Solid, mg/L	995 ± 10

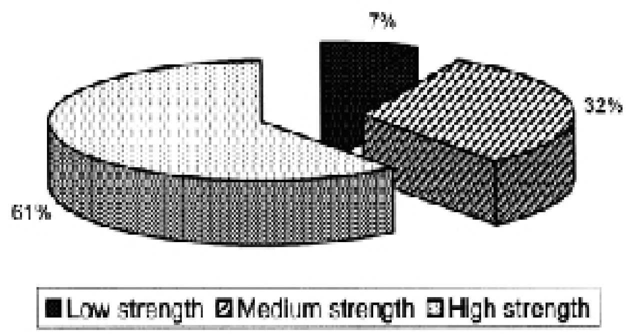

Fig.1 Relative proportion of work done during 1999-2010 on the treatment of industrial wastewaters of different strengths by UASB reactors (fraction of papers published out of a total of 108).

Wastewater from the dairy industry is generally produced in an intermittent way, and the flow and characteristics of wastewaters changes from one industry to another depending on the kind of systems and the methods of operation (Rico *et al.* 1991). The end of pipe effluent of the Sanchi Dairy (Ujjain Dugdh Sangh Maryadit, Ujjain, M.P., India), which is run by Madhya Pradesh State Cooperative Dairy Federation Ltd. and is located in South-East direction of Ujjain (Madhya Pradesh) city, situated 10 Km from the laboratory was used as influent in UASB. The main characteristics of the DWW, i.e. the feed of the anaerobic digestion system, are given in Table 1.

Inoculum sampling and characterization

A digested cow-dung slurry (DCDS), obtained from a mature biogas-digester plant from Hameer Khedi village, district Ujjain, M.P. and earthworm cultured soil (ECS), was used as inoculum. The characteristics of innoculum used were pH of 6.8, TS of 760 g/L, SS of 220 g/L ,VSS of 180 g/L. A substantially higher level of TS as compared to VSS was due to the inert materials with higher specific gravity.

Reactor start-up

The start-up period of an anaerobic UASB reactor is directly proportional to the concentration of the microbial population and the rate of start-up depends on the type of inoculums and the type and strength of wastewater. Anaerobic sludge mass for UASB reactor was developed by stabilizing the digested cow dung slurry (DCDS) and earthworm cultured soil (ECS). During stabilization, the UASB reactor was hydraulically experimented with synthetically prepared wastewater, before addition of inoculums. At first, separator action was ignored to separate the heavy and light granules easily. After 5 weeks (10 March - 14 April) of bacteria growth, the inoculums were added to the reactor. The UASB reactor used as methanogenic reactor was seeded with 4.5 L of DCDS and ECS, giving a settled sludge-bed height of 25.4 cm. The reactor was then allowed to stabilize for 24 h at 20 - 42 °C in order to allow the bacterial community to acclimatize and fed with DWW and nutrient rich DWW as additional seeds. The volume of the sludge was reduced about 33% due to the settlement of the sludge bed during these 24 h. DWW was then introduced into the reactor to acclimatize the sludge.

During startup, before feeding the DWW, synthetically prepared DWW were also added to provide nitrogen, phosphorous source and alkalinity buffering for anaerobic digestion. Table 2 gives the composition of nutrients, added to prepare synthesis DWW. No multivalent cations other than those present in the yeast extract were added to the media. The mixture (synthesis DWW) has been kept for 3 weeks at 20 - 42 °C temperature for growing the anaerobic bacteria before addition to DWW. Thereafter, this mixture has been used as additional seeds at the rate of 2 mL/ Lfor anaerobic treatment. In addition, the pH of influent and inoculum both were adjusted to around 7.0 with alkaline solution ($NaHCO_3$) to optimize the environment for maximum granule growth. Feeding of influent was maintained at loading rate of 2.77 kgCOD/m^3d until the reactor started producing gas. The reactor's performance were assesed before an after required HRTs of 6, 12, 24 and 48 h. The steady state condition was determined when the standard deviation values of removal efficiency were less than 5%. It took about 6 days for the UASB reactor to achieve stability and 3 days to start producing methane gas.

Table 2. Composition of nutrients in synthetically preapared DWW

Compound	Concentration (g/L)
$NaHCO_3$	5.0
NH4Cl	3.0
KH_2PO_4	1.5
Lauryl Tryptose broth	0.5

Operational Conditions during the study

pH: pH of around 7.0 has been maintained in present experimental work.

Temperature: The experiments have been performed at mesophilic (20 - 42°C) range of temperature.

Hydraulic Retention Time: To study the effect of HRT on the process performance, the reactors were operated at various HRTs i.e., 6, 12, 24, 48 and 72 h.

Organic Loading Rate: The OLRs corresponding to various HRTs of 6, 12, 24, 48 and 72 h, were kept at 2.77, 2.16, 1.57, 1.052 and 0.54 kgCOD/m^{3}d and 1.276, 0.995, 0.741, 0.515, 0.261 kgBOD/m^{3}d respectively, due to changes in influent composition.

Superficial Upflow Velocity: The superficial upflow velocity was maintained constant at 0.0224 m/h.

Pilot scale UASB reactor design and operation

Pilot scale UASB reactor experimental setup

A pilot scale UASB reactor was fabricated with transparent PVC sheet (to avoid corrosion) using leak proof sealing along reactor and along with proper inlet and outlet arrangements to maintain anaerobic conditions inside the reactor. A typical UASB reactor consists of three parts; 1) sludge bed, 2) sludge blanket and 3) a three-phase separator known as a gas-liquid-solid (GLS) separator. The height and inner diameter of the reactor were 103.6 and 15 cm respectively and a small funnel installed in the upper part acting as a GLS separator and an influent distributor at the base in order to reduce clogging problems. The GLS separator at the top was made of non-transparent galvanized iron sheet and was provided at a distance of 79.2 cm from the bottom. Furthermore, two baffles have been provided inside the reactor to guide gas bubbles into the separator, to collect the gas generated and to allow the settling of suspended solids. Lower half of the GLSS was inclined entity with a slope angle (Ø) of 45^0, whereas upper half was a tubular section with an outside diameter (OD) of 1.9 cm and an inside diameter (ID) of 1.27 cm. Three taps are provided at different heights of 17.8, 53.3 and 66.0 cm, enabled effluent and sludge sampling. The top of reactors was connected to gas collector bottle using a water displacement container filled with an Alkaline (NaOH) solution to prevent CO_2 dissolution (Borja *et al.* 1996). Fig. 2 shows Schematic diagram of UASB Experimental Setup.

Experimental Operations of Pilot Scale UASB Reactor

The formation of anaerobic granular sludge can be considered as the major reason of the successful introduction of the UASB reactor concept for anaerobic treatment of DWW. After achieving the steady state condition of UASB reactor, 9.5 L of DWW was introduced at the bottom of the reactor through a tube with a 12.7 mm diameter, distributed over the cross-section and passed upward through the granular sludge bed at the upflow velocity of 0.0224 m/h. The organic matter is then converted to methane and carbon dioxide and leads to the formation of gas bubbles which can provide adequate mixing and wastewater/biomass contact. The granules rise in the reactor due to the bubbles, however they will settle in the tank since their settling velocities are greater than the upflow velocity (typically 1m/h). To capture suspending particles and reduce their washout effciently, an enlarged portion termed as gas- liquid- solid (GLS) separator was added at the top of the column, giving the reactor a total height of 103.6 cm and a total volume of 18 L. However, The effective volume of the reactor was 14.0 L. During experiment, the synthetically prepared DWW was also added to the reactor, as was being added during startup. The gravity force was used for the entry of DWW to the reactor to prevent the fouling of entry tubes and air entry to reactor.

This experiment, after UASB startup, was operated for 34 days at 20 -42°C temperature in a climate room to treat DWW and to produce biogas from it. The experimental study was operated at batch mode. It should be mentioned that the average wastewater temperature and pH were monitored daily and were adjusted to around 7.0. At steady state the reactor effluent was sampled after every batch of required HRTs and OLRs for pH, temperature, COD and BOD_5 analysis. Also, CH_4 gas production were observed and tested daily. Also, DWW sample was diluted using tap water to OLR prior to feeding and pH adjustment. The UASB system was operated for 44 days (14 April- 27 May) including 10 days for reactor startup (14 April - 23 April) and 34 days of experimental operation (24 April - 27 May) after steady state and was tested at the different HRTs of 6, 12, 24, 48 and 72 h.

Analytical methods

All the samples, chemical solutions and experiments were prepared using ultrapure water. Grab samples of the influent thus collected were analyzed for 7 physico-chemical-biological parameters viz. pH, COD, BOD_5, SCOD, $SBOD_5$ TS and SS as per the methods described in "standard methods for the examination of water and waste water" American Public Health Association (APHA, 1992), Listed in Table 3. And the effluents of the UASB reactor were sampled for pH and COD analysis. Samples were collected in duplicate and the sampling duration was ½ an h. 1 L

Table 3. Analytical Methods Used for evaluation of various parameters

Parameters	Analytical Method as per Standard methods,1992,18th Edition
pH	423 pH meter (LI 614 ELICO pH analyzer)
COD (Soluble and Total)	508 A. Open Reflux Method
BOD_5 (Soluble and Total)	507 Five Days incubation at 27°C followed by 421 B. Azide Modification
Total Solid	209 A. Total Solids dried at 103 -105°C
Suspended Solid	209 C. Suspended Solids dried at 103-105°C
Volatile Suspended Solid	209 D. Volatile Suspended Solid ingnited at 550°C

Table 4. Typical values for the performance of UASB reactor during the different phases of experiments

Days of Experiments	Q (L/d)	HRT (h)	Velocity (m/h)	OLR (kg COD/m3.d)	OLR (kg BOD/m3.d)	Effluent pH	max.COD η (%)	max. BOD η (%)
1-3	9.5	6	0.0224	2.770	1.276	7.5	23.3	32.5
4-7	9.5	12	0.0224	2.160	0.995	7.1	33.1	46.7
8-13	9.5	24	0.0224	1.570	0.741	7.9	47.3	58.5
14-25	9.5	48	0.0224	1.052	0.515	7.4	64.0	73.3
26-34	9.5	72	0.0224	0.540	0.261	7.7	62.8	71.6

sample of both influent and UASB effluent were collected in sterilized bottle and were protected from direct sunlight during transportation. All samples were stored under refrigeration at 4 °C until analyzed and after proper preservation immediately transported to the Pollution Control Board (PCB), Ujjain to evaluate selected parameters. The samples were analyzed within 4 hrs of collection. Due to the lack of facilities, TKN, Total and faecal coliform count and gas composition were not measured.

RESULTS AND DISCUSSION

Performance of the UASB reactor

The performance of the UASB reactor in terms of COD and BOD_5 depends on temperature, HRTs and OLRs. Experiments were performed in the mesophillic (20 - 42 °C) range of temperature. Typical values for the performance of UASB reactor during the different phases of experiments are depicted in Table 4.

Performance of UASB reactor during startup

During startup the reactor was operated at HRTs of 6, 12, 24 and 48 h. Feeding of influent was maintained at loading rate of 2.77 kgCOD/m^{3}d until the reactor started producing gas. The reactor's performance were assesed before and after required HRTs. As can be seen from Fig. 3, in the experiment carried out with the UASB reactor, the maximum COD removal efficiency of 21% was achieved at an optimum HRT of 48 h, on 10th day. The steady state condition was determined when the standard deviation values of removal efficiency were less than 3% i.e, at HRT of 24 h it was 19% and at 48 h it was 21%.

COD and BOD removal efficiencies under varying HRTs

UASB reactor was exposed to various HRTs including 6, 12, 24, 48 and 72 h. As can be seen from Fig. 4, in the experiment carried out with the UASB reactor, the maximum COD and BOD_5 removal efficiency of 64.0% and 73.3 % was achieved at an optimum HRT of 48 h. It was observed that by raising the HRT from 6 to 48 h, the performance of the system is improved. But by raising the HRT from 48 to 72 h the difference is not meaningful. Beyond a HRT 48 h marginal decrease in COD and BOD_5 removal was noticed and the efficiency of pilot dropped in days leading 26-34. Low COD and BOD_5 removal efficiency in HRTs less than 48 h is probably owing to the less stabilized character of the sludge resulting in a stronger tendency for flotation (Van Haandel and Lettinga, 1994). Also, further increase in HRT above 48 h did not lead to a significant increase in COD and BOD_5 removal efficiency. This is probably attributed to the fact that a long HRT above 48 h might lead to a low concentration of fermentative substrates (Stronach *et al.* 1986).

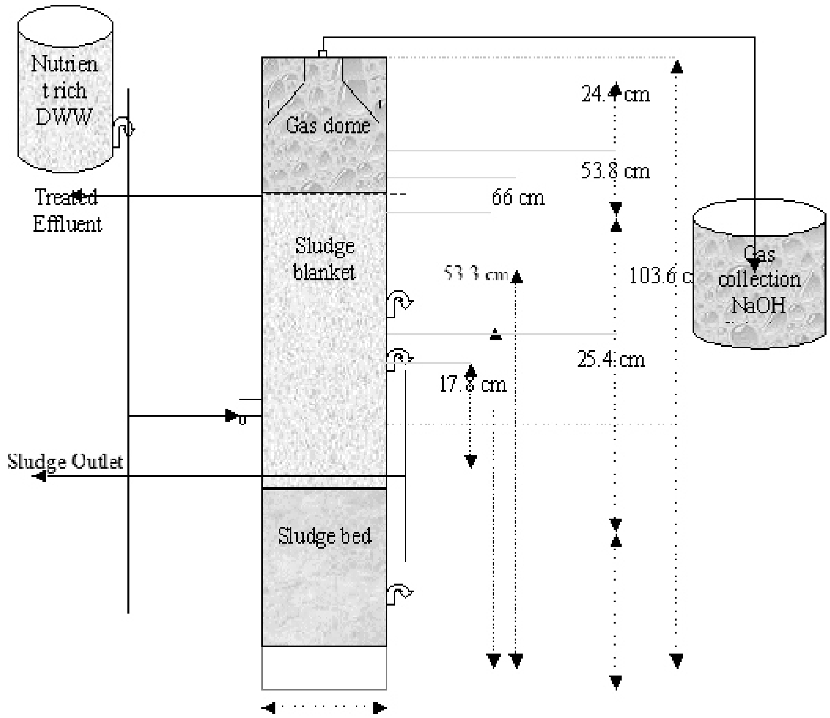

Fig. 2 Schematic diagram of UASB Experimental Setup

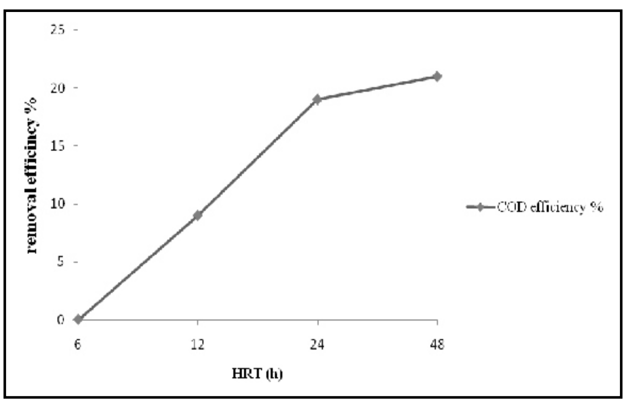

Fig. 3 COD removal efficincy under varying HRTs and constant OLR during startup

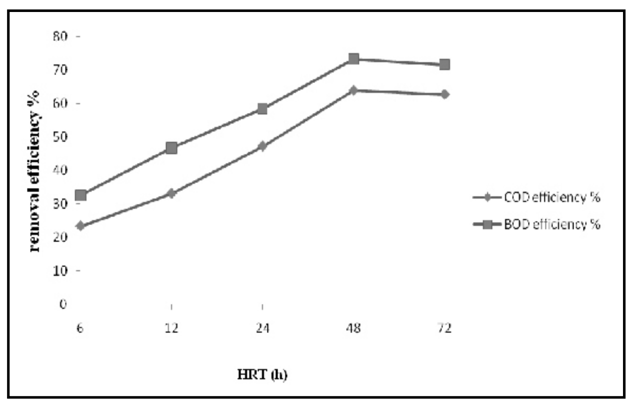

Fig. 4 COD and BOD removal efficiencies under varying HRTs

COD and BOD removal efficiencies under varying OLRs

The OLRs corresponding to various HRTs were kept at at 2.77, 2.16, 1.574, 1.052 and 0.54 kgCOD/m^{3}d and 1.276, 0.995, 0.741, 0.515 and 0.261 kgBOD/m^{3}d respectively, due to changes in influent composition. The organic load applied to the reactor at maximum COD and BOD removal efficiencies were 1.052kg COD/m^3.d and 0.515 kgBOD/m^3.d respectively (Fig. 5 and 6), with an influent and effluent COD concentration of 1550 mg/L and 557 mg/L and influent and effluent BOD5 concentration of 759 mg/L and 202.6 mg/L respectively.

Variation in OLRs and pH at different HRTs

With increase in HRTs from 6 h to 72 h the OLRs of COD and BOD5 decreases, depicted in Fig. 7. The pH of the treated wastewater was in the range of 7.1 - 7.7 at different HRTs, depicted in Fig. 8, which is indica-

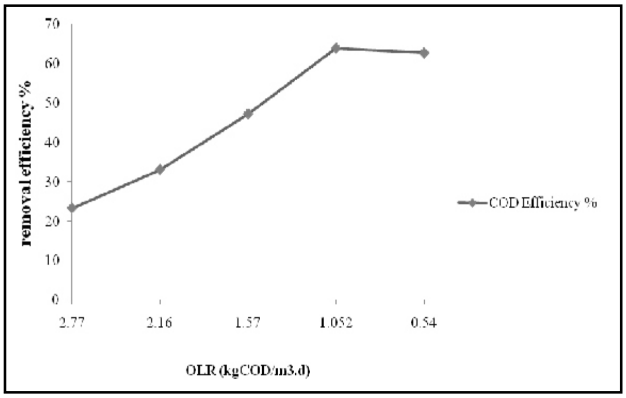

Fig. 5 COD removal efficiency under varying OLRs

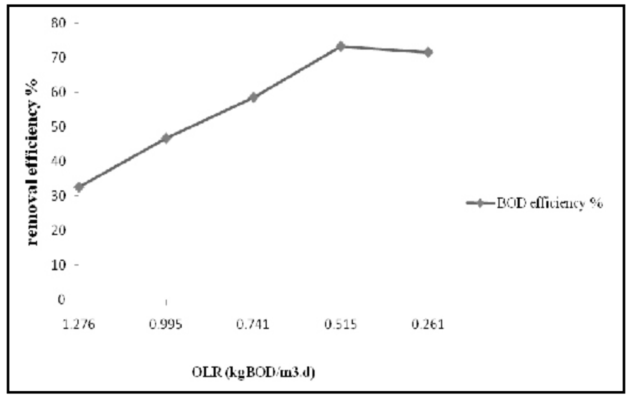

Fig. 6 BOD removal efficiency under varying OLRs

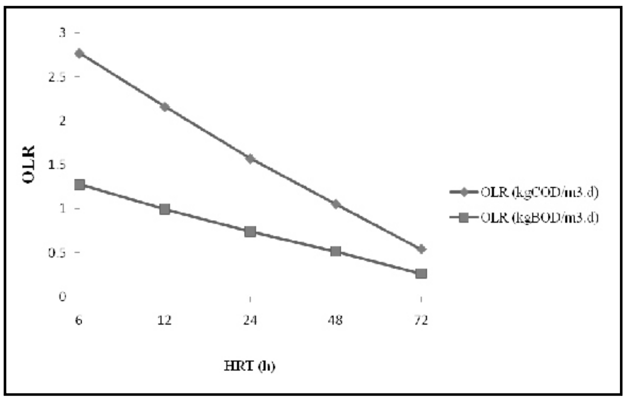

Fig. 7 Variation in OLRs at different HRTs

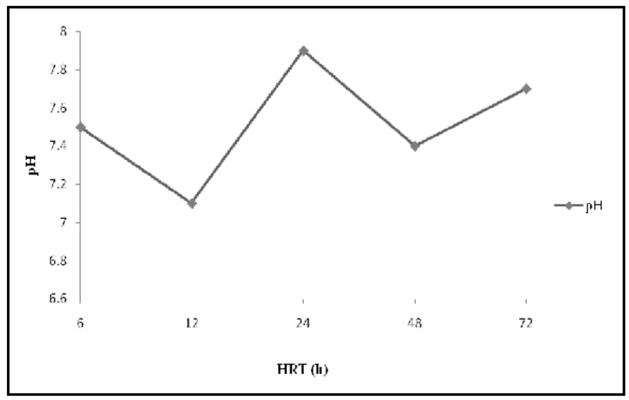

Fig. 8 Fig 5 Variation in pH at different HRTs

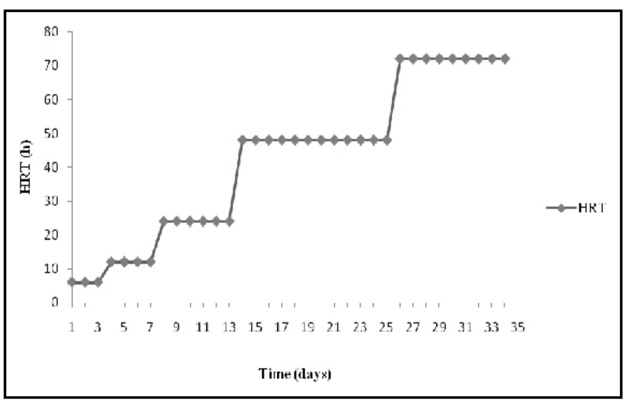

Fig. 9 Variation in HRTs over time

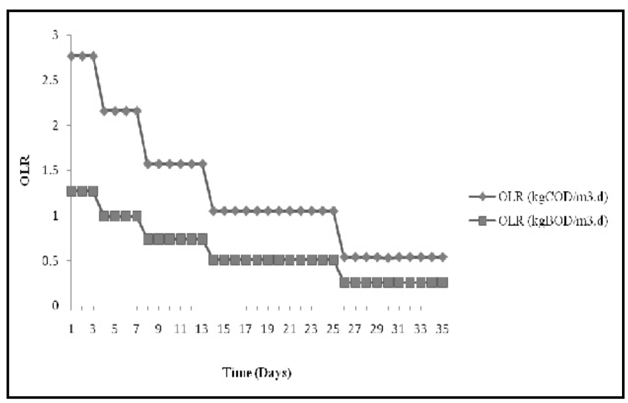

Fig. 10 Variation in OLRs over time

tive of active metabolism of the methanogens and satisfactory condition of the reactor. Because the best operation of anaerobic reactors can be expected when, the pH is maintained near neutrality (Lettinga, 1980). It is known that pH value less than 6.8 and greater than 8.3 would cause souring of reactor during anaerobic digestion (Wheatley *et al.* 1991; Metcalf and Eddy, 2004).

Variation in HRTs and OLRs over time

From day 1st to 34^{th} day HRTs were increased from 6 h to 72 h as shown in Fig. 9 and OLRs were decreased from 1.276 kg BOD/m^3.d to 0.261 kgBOD.m^3.d and 2.77 kgCOD/m3.d to 0.54 kgCOD.m3.d as shown in Fig. 10.

CONCLUSION AND RRECOMMENDATIONS

The experimental results obtained in this investigation demonstrate that the UASB reactor is efficiently feasible for treatment of DWW. Due to the nature of wastewater, it was preferred to add light nutrient. The efficiency of the pilot has been gradually rising through course of time, because it has achieved the percentage removal of 73.3 % for BOD. However, the BOD concentration in the effluent of the anaerobic treatment step generally does not comply with standards for discharge into receiving water bodies. Therefore, post-treatment is required. Some adequate post-treatment have to be applied for entire removing of pollutants from the effluent. The combination of a UASB and AS system would be a very promising option for the treatment of DWW. This combined system can satisfy standards required for discharge of effluents into agricultural drains and receiving water bodies. It has also been revealed that reduction of alkalinity can lead to lower efficiency of reactor.

Appendix. Notation

Symbols

BOD	Biochemical Oxygen Demand, mg/L
COD	Chemical Oxygen Demand. mg/L
HRT	Hydraulic Retention Time, h
OLR	Organic Loading Rate, kgBOD/m^3.h and kgCOD/m^3.d
h	hour

Abbreviations

UASB	Upflow Anaerobic Sludge Blanket
DCDS	Digested Cow Dung Slurry
DWW	Dairy Waste Water
ECS	Earthworm Cultured Soil
PVC	Poly Vinyl Chloride
GLS	Gas Liquid Separator

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