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Development of a Hybrid Anaerobic Bioreactor for Treatment and Energy Conversion of Organic Effluents

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Abstract

Many agro-processing industries like cassava starch factories cause pollution of air and water due to the discharge of untreated organic effluents. Often, these industries face shortage of fuels for providing the process heat. Anaerobic treatment of agro-industrial effluents is an eco-friendly alternative for conversion of these liquid wastes to energy in the form of methane. Up-flow anaerobic hybrid reactors (UAHR) for treatment of cassava starch factory effluent (CSFE) were designed and fabricated with preprocessed coconut shells as media and was evaluated in comparison to another bioreactor with PVC pall rings media by operating the system at different hydraulic retention times (HRT). The performance of the bioreactors were found to be satisfactory in their ability for pollutant reduction and energy (biogas) production. Subsequently, similar lab scale bioreactors with coconut shells as well as rubber seed outer shells as media could be successfully used for Rice Mill Effluent (RME). Even though a slight inhibitory effect was observed in the case of coconut shells during the start-up the developed UAHR was found to be effective in pollutant reduction and energy conversion in the case of RME also. Based on these successful experiences, a pilot scale UAHR was installed for biomethanation of waste coconut water (WCW) from a coconut oil mill. The system was operated successfully for four months at a hydraulic retention time of five days. The cost reduction achieved by replacement of synthetic media with locally available natural materials as well as the simple design coupled with high treatment efficiency and biogas production ability offers great scope for energy conversion of these agro-industrial effluents.

Key words: Biomethanation, cassava starch factory effluent, agro-industrial effluent, cell immobilization, up-flow anaerobic hybrid reactor

Introduction

Agro-processing industries like cassava starch factories, rice mills and coconut oil mills result in the production of organic effluents. Cassava starch factory effluent (CSFE), rice mill effluent (RME) as well as waste coconut water (WCW) are often not properly treated and results in air and water pollution. At the same time, thermal energy produced from fire wood is used for process heat requirements in these industries. The anaerobic treatment of these organic effluents has the twin advantages of pollution control and production of energy as biogas. As anaerobic treatment of high volume low strength liquid wastes can be undertaken only by the use of high-rate anaerobic bioreactors, it was attempted to develop an environmentally benign bioreactor for their treatment and energy conversion.

Materials and Methods

Two field scale up-flow anaerobic hybrid reactors for treatment of CSFE were designed and fabricated (James, 2000). Reactor I had preprocessed coconut shells as media and reactor II had PVC pall rings as media. A hybrid design was evolved based on the basic principles of anaerobic bioreactors described elsewhere (Lettinga and Pol, 1986 ; Young, 1991; Podruzny and Mc Lean, 1989) and incorporating the Up-flow Anaerobic Sludge Blanket (UASB) and Up-flow Anaerobic Filter (UAF) concepts (James, 2000, James and Kamaraj, 2002a). Promising results of anaerobic digestion of CSFE from previous studies (James and Kamaraj, 2002b) encouraged the development of a high rate bioreactor. The bio-reactors were fabricated with coconut shells as media for cell immobilization based on previous studies (James and Kamaraj, 2004) and was installed in a sago factory and their ability for pollutant reduction and energy (biogas) production were evaluated by monitoring the influent and effluent characteristics (pH, biological oxygen demand (BOD) and chemical oxygen demand (COD), daily biogas production and biogas quality (APHA, 1989).

The biomethanation characteristics of RME and the compatibility of the different media to be used for cell immobilization viz., rubber seed inner shell, coconut shell and rubber seed outer shell were carried out with 12 treatments in 10 l plastic digesters attached with 3 l capacity water displacement meters. Eight up-flow anaerobic hybrid reactors (UAHR) for a design hydraulic retention time (HRT) of one day, with media on the upper half of the reactor was designed and fabricated. The evaluation comprised of four treatments viz. reactors R_1, R_2 and R_4 with rubber seed outer shell as media, and R_3 having polyurethene rings (inert media), each replicated twice. Fresh cow dung mixed with water having a total solids (TS) of 3% was used as inoculum in reactors R_1 (volume 20%) as well as R_3 and R_4 (volume 50%). Sludge from semi-continuous digesters was used as inoculum in R_2 (volume 20%) so as to test its performance against cow dung. A computer controlled peristaltic pump was used for feeding at different HRTs. The UAHRs were evaluated from the volume and methane content of biogas as well as pH, TS, BOD and COD of influent and effluent by operating them at different organic loading rates (OLR) and hydraulic loading rates (HLR) corresponding to HRTs of 10, 5, 3, 2, 1 and 0.8 day.

A pilot scale UAHR was fabricated and installed in a coconut oil mill. The total liquid volume of the bioreactor was 350 l. The media for cell immobilization was coconut shells, placed at the upper half of the reactor. The bioreactor was started up in dilute cow dung slurry mixed with waste coconut water at a start-up HRT of 20 days. The HRT was successively reduced to attain a final HRT of five days.

Subsequently a full scale bioreactor was constructed for treatment of 250 l of waste coconut water per day. The material used for construction was concrete. The total volume of the bioreactor was 1.15 m^3 with a liquid volume of 1 m^3. The upper 60% of the reactor volume was filled with coconut shell media with a porosity of 0.75%. The full scale bioreactor was started up with the sludge from pilot scale bioreactor mixed with out-flowing slurry from a cow dung based biogas plant. The bioreactor was started up successfully without the use of alkali and was operated at an HRT of four days. The system had a separate gas collection unit with a masonry cylindrical tank and a Fibre Reinforced Plastic (FRP) gas holder. The gas production was measured using a wet gas flow meter.

Results and Discussion

Preliminary investigations on the characteristics revealed that the effluents became highly acidic due to natural fermentation reactions in the collection tank. These effluents had a pH in the range of 3.8-5.2. The TS, BOD and COD values were in the range 3900-4650, 2650-4025 and 5515-7060 mg l^{-1} respectively. The carbon: nitrogen (C:N) ratio was 20.4-32.5 :1.

The pilot scale bioreactors for CSFE, one with coconut shell media (Reactor I) and a similar one with PVC pall rings (Reactor II) were started up at a HRT of 15 days. The reactors were allowed to reach a pseudo steady state condition and then the HRTs were successively reduced. The variations in hydraulic as well as organic loading rates at different HRTs are shown in Fig.1. The pollutant reductions in terms of TS, volatile solid (VS), BOD and COD of the UAHRs at various HRTs are shown in Table 1. Very high reductions of 99 and 98.9% for reactors I and II were obtained at the longest HRT of 15 days. The BOD reductions went down with the decrease of

Table 1. Reactor performance at pseudo-steady state of different hydraulic retention times for cassava starch factory effluents

Parameters		Hydraulic retention time (days)							
		15	11	8	6	4	2.5	1.67	1
Total solid reduction (%)	Reactor I	60.0	57.2	56.7	55.5	50.5	46.1	40.3	33.8
	Reactor II	59.3	56.8	55.6	55.1	49.5	44.9	38.1	32.4
Volatile solid reduction (%)	Reactor I	76.2	75.3	75.9	70.6	65.7	59.9	53.8	49.5
	Reactor II	75.9	74.7	75.4	69.9	64.5	58.6	52.4	48.0
Biochemical oxygen demand reduction (%)	Reactor I	99.0	98.6	98.8	98.6	95.6	87.5	83.0	78.9
	Reactor II	98.9	98.3	98.3	98.2	94.4	85.8	82.4	77.4
Chemical oxygen demand reduction (%)	Reactor I	96.2	96.4	96.2	96.1	93.2	86.3	81.8	77.4
	Reactor II	96.0	96.3	95.8	95.2	92.0	85.0	80.5	76.0
Methane (CH_4) content of biogas (%)	Reactor I	70.0	71.0	72.0	72.0	70.5	68.0	66.0	65.0
	Reactor II	72.0	73.0	74.0	73.0	71.0	68.5	65.0	64.0

HRT but the decrease in reduction was mild up to 6 day HRT. There after the decrease was rather sharp due to the steep hike in the HLR. The lowest reduction of 78.9 and 77.4% BOD occurred at 1 day HRT. Reactor I was found slightly superior to reactor II in BOD reduction at all HRTs.

The mean daily gas productions of reactors registered an increase of 7.8 and 8.2 times respectively for reactor 1 and 2 when the HRT was reduced from 15 days to 1 day, while the specific gas productions (l kg^{-1} TS) decreased from 909 l (at 15 day HRT) to 574 l (at 1 day HRT) for reactor I (Table 2). For reactor II, the

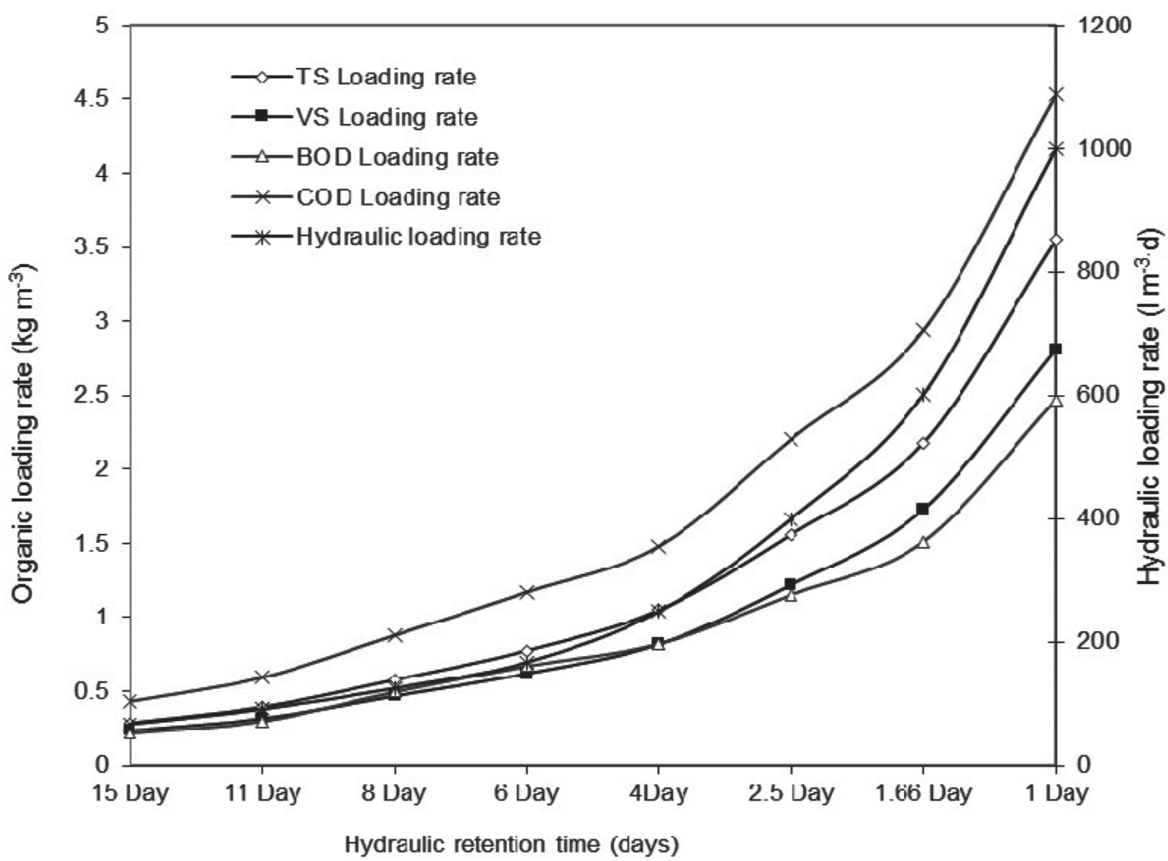

Fig 1. Hydraulic and organic loading rates at different HRTs

Table 2. Reactor performance in the treatment of cassava starch factory effluents

Parameters		Hydraulic retention time (days)							
		15	11	8	6	4	2.5	1.67	1
Biological oxygen demand reduction (%)	Reactor I	99.0	98.6	98.8	98.6	95.6	87.5	83.0	78.9
	Reactor II	98.9	98.3	98.3	98.2	94.4	85.8	82.4	77.4
Specific gas production ($l\ kg^{-1}$ TS added)	Reactor I	909	903	919	881	822	775	723	574
	Reactor II	845	826	902	871	787	726	680	556
Biogas productivity ($l\ l^{-1}$ feed)	Reactor I	3.90	3.90	4.24	4.10	3.45	3.02	2.62	2.04
	Reactor II	3.63	3.60	4.16	4.05	3.30	2.83	2.47	1.98
Volumetric gas production ($l\ m^{-3}$ reactor)	Reactor I	260	356	527	683	863	1210	1576	2038
	Reactor II	242	325	521	675	826	1132	1485	1975
CH_4 content of biogas (%)	Reactor I	70.0	71.0	72.0	72.0	70.5	68.0	66.0	65.0
	Reactor II	72.0	73.0	74.0	73.0	71.0	68.5	65.0	64.0

corresponding figures were 845 and 556 $l\ kg^{-1}$ TS. The per cent decrease over initial values were 36.8 and 34.1, respectively for reactors I and II. It is evident from Fig. 2 that the volumetric gas production increased sharply with reduction in HRT for both the reactors, while the biogas productivity got reduced as the HRT was shortened. The CH_4 content of biogas was in the range 64-74%.

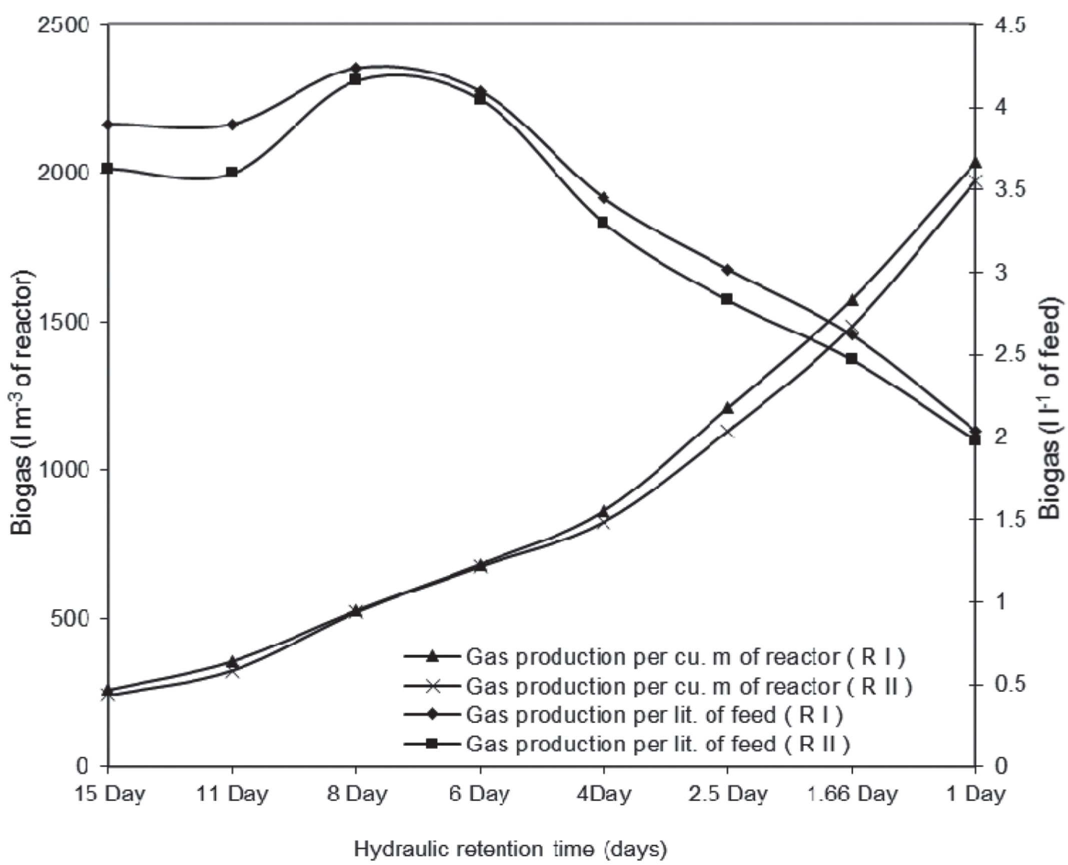

Fig 2. Volumetic biogas production at different HRTs

The eight lab scale UAHRs were designed and fabricated for the treatment of RME. They had a total height of 60 cm and a diameter of 20 cm. The media was placed at the upper half of the reactor, retained at the proper position by dispersion plates and had a height of 29.5 cm for the media filled portion. The sludge bed zone consisted of the bottom 29.5 cm height of the reactors.

The start-up characteristics revealed that 23 to 25 days were required for the startup. The bioreactor with 50% inoculum volume was observed to get started up early, but 20% volume of inoculum was sufficient for start-up. No difference was observed with respect to the use of reactor sludge as inoculums over cow dung. The effluent characteristics of all the reactors with respect to TS, BOD and pH reached steady state in this period showing good stability of the reactors. The HLR of the reactors during 10 day HRT period was 100 l m^{-3} with an OLR of 0.164 kg TS m^{-3}d. All the reactors showed good gas production performance and the highest specific gas production of 1299 l kg^{-1} TS and 591 l kg^{-1} BOD were observed in the UAHR with rubber seed outer shell as media. The performance of the reactors with respect to TS and BOD reductions were in the range of 58.5 to 61.1 and 81.7 to 82.9%, respectively. The evaluation of the reactors conducted by operating them at HRTs 10 day, 5 day, 4 day, 3 day, 2 day, 1 day and 0.8 day further confirmed the stability of operation and high performance of the UAHRs. The effluent pH values were in the range 7.0–8.6 during the entire period of operation even though the influent had a low pH in the range 3.8–3.9. The effluent TS and BOD were found to increase with the reduction of HRT for all reactors. The methane content of biogas reached the peak value of 75% at 4 day HRT in Reactor 1. The OLRs during steady state periods of 10 day to 0.8 day HRT progressively increased to reach the peak values of 2.2 kg TS m^{-3}.d and 4.4 kg BOD m^{-3}.d for all the reactors at 0.8 day HRT. The HLRs also increased in a similar way from 100 to 1250 l m^{-3}.d. The specific gas productions in terms of TS and BOD for all reactors were found to decrease with the reduction of HRT. The biogas productivity (l l^{-1} of RME fed) also followed a similar trend of specific gas production. The volumetric gas production increased with the decrease of HRT in all reactors. The maximum production of 854.9 l m^{-3} was observed in R_1 at 0.8 day HRT while the lowest production (122 l m^{-3}) was observed by R_3 at 10 day HRT. The TS and BOD reductions followed a decreasing trend with shortening of HRT. The maximum reductions were 61.1% TS by R_1 and 82.9% BOD for R_4, respectively, both at 10 day HRT. The minimum values were observed at 0.8 day HRT ie. 34.1% TS (R_4) and 77.1% BOD (all reactors). The high performance of the developed bioreactors could be accounted to the high degree of cell immobilisation obtained by the hybrid design, which incorporated the sludge blanket concept along with media peaking. The reactor with rubber seed outer shell media was found to perform better than the reactor with polyurethane media, possibly due to the more favorable micro structure of rubber seed shell surface, which facilitated biomass attachment.

The pilot scale UAHR installed in the coconut oil mill was started up with the out flowing slurry from a cow dung based biogas plant. The waste coconut water had a pH ranging from 3.8 to 5.5 during the study period. The TS ranged from 3400 to 4200 mg l^{-1}. A biogas productivity of 1.8 and 2.4 l l^{-1} of waste coconut water was obtained at the hydraulic retention times of 4 and 6 days, respectively (Fig. 3). The volumetric biogas production was 300 and 350 l m^{-3} reactor volume at HRTs 6 and 4 days respectively.

The full scale bioreactor was started-up in a short period of 20 days and became operational at an HRT of 6 days and was subsequently reduced to 4 days. The average biogas productivity was 2.45 l l^{-1} of waste coconut water. The volumetric biogas productions were 550 and 420 l m^{-3} reactor volume at HRTs of 4 and 6 days, respectively. Even though the influent waste coconut water had a pH in the range of 4.5-5.5, the effluent had a pH in the range of 7.2-7.4. The bioreactor was found to operate in a stable condition irrespective of the variation in influent pH. Even though the possibility of using ligno-cellulosic materials in high rate bioreactors were studied in early days (Nordstedt and Thomas, 1985) further development in this area was not seen done. The performance of coconut shells as well as rubber seed outer shells were found promising in these studies.

Conclusion

The designed up-flow anaerobic hybrid reactors (UAHR) performed well for the treatment of cassava starch factory effluent, rice mill effluent as well as waste coconut water in both the aspects of pollution control and energy

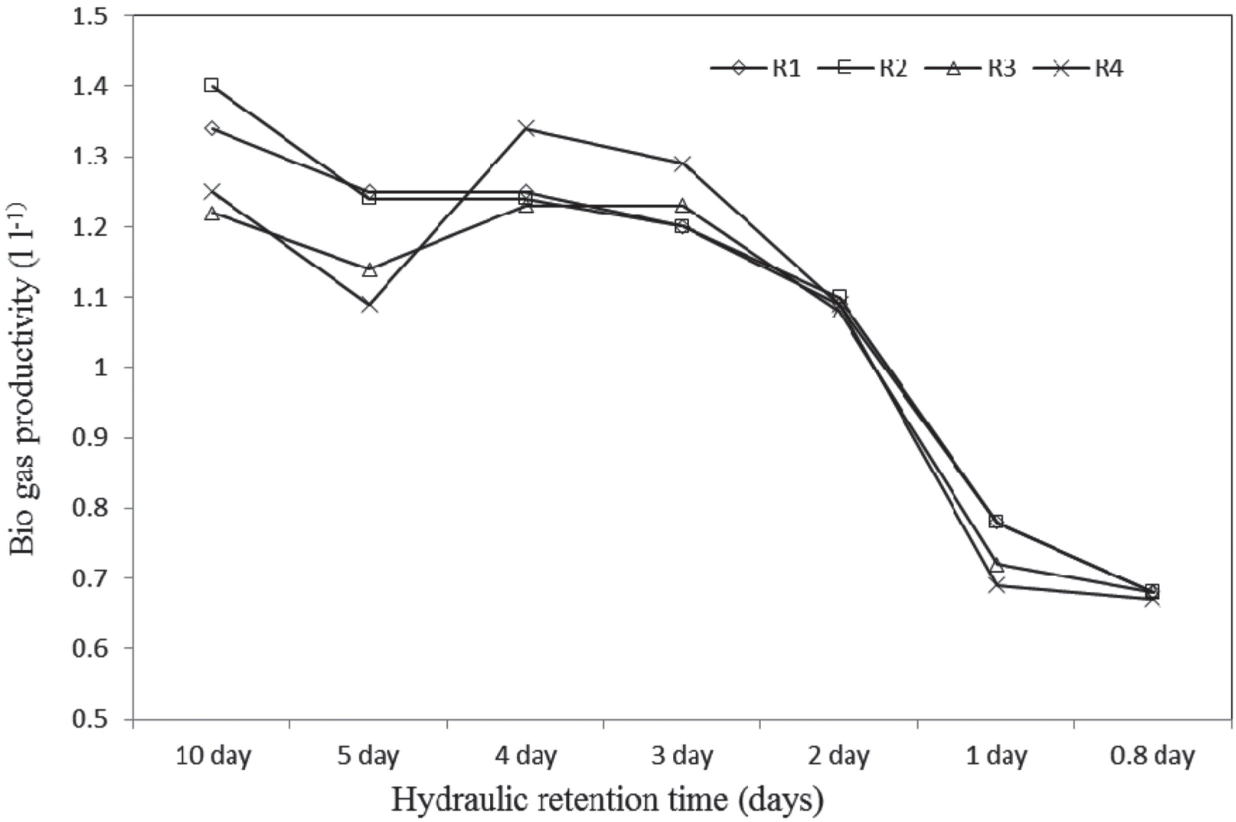

Fig 3. Biogas productivity of UAHRs at different HRT periods.

production. The coconut shells could be successfully used as matrix for cell immobilization in the designed UAHR but a slight inhibitory effect was observed during the start-up, which needed some pretreatments. The compatibility of naturally available agricultural byproducts like coconut shells and rubber seed outer shells was promising. The fabrication cost of the bioreactors can be tremendously reduced by using coconut shells as matrix in comparison to PVC matrix. The low cost and simple design of the UAHR coupled with high treatment efficiency and gas production ability offers great scope for energy conversion of a wide range of agro-industrial effluents.

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