INVESTIGATIONS ON HIGH RATE ANAEROBIC BIOREACTOR FOR ENERGY PRODUCTION FROM RUBBER LATEX PROCESSING EFFLUENT

by

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MEGHA A. S.

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2020

DECLARATION

I hereby declare that this thesis entitled **'Investigations on high rate anaerobic bioreactor for energy production from rubber latex processing effluent'** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or associateship or other similar title of any other University or Society.

Place: Tavanur

Date: 04-01-2021

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CERTIFICATE

Certified that this thesis entitled **'Investigations on high rate anaerobic bioreactor for energy production from rubber latex processing effluent'** is a bonafide record of research work done independently by Ms. Megha A. S. under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to her.

Place: Tavanur

Date: 04-01-2021

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CERTIFICATE

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SYMBOLS AND ABBREVIATIONS

AC	:	Alternating Current
AF	:	Anaerobic Filter
AFBR	:	Anaerobic Fluidized Bed Reactor
APHA	:	American Public Health Association
BOD	:	Biochemical Oxygen Demand
COD	:	Chemical Oxygen Demand
D	:	Day
DC	:	Direct Current
DO	:	Dissolved Oxygen
HLR	:	Hydraulic Loading Rate
HRT	:	Hydraulic Retention Time
ID	:	Internal Diameter
Min	:	Minute
OLR	:	Organic Loading Rate
PSS	:	Pseudo Steady State
PVC	:	Poly Vinyl Chloride
RLPE	:	Rubber Latex Processing Effluent
SMPS	:	Swich Mode Power Supply
TS	:	Total Solids
UAF	:	Up-Flow Anaerobic Filter
UAHBR	:	Up-Flow Anaerobic Hybrid Bioreactor
UAHR	:	Up-Flow Anaerobic Hybrid Reactor
UASB	:	Up-flow Anaerobic Sludge Blanket
VFA	:	Volatile Fatty Acid
VS	:	Volatile Solids
VSS	:	Volatile Suspended Solids
v/v	:	volume/volume

INTRODUCTION

Chapter I

INTRODUCTION

Currently high amounts of industrial effluents are discharged as a consequence of increased industrial activities worldwide. As a developing country, industrial pollution is increasing at an alarming rate along with population in India. Agro-processing industries also contribute significantly in pollution due to effluent discharge. Agro-processing effluents are often discharged to local water bodies and nearby land creating environmental issues locally. Small and medium scale food process industries find it difficult to manage these waste waters which may contain organic, inorganic, suspended and dissolved solids. Generally they have high biochemical and chemical oxygen demands. Unregulated management of these waste waters also results in environmental problems leading to human health problems. In order to minimize the risk to the environment and public health, there is a need for proper treatment processes for agro-industrial effluents.

Waste to energy is a source of renewable energy and energy recovery from wastes involves ecological advantages like minimizing the consumption of fossil fuels like coal, oil etc. Reductions in carbon emission and fossil fuel use are benefits of energy recovery from wastes. Alternative and environment friendly methods for generating process heat as well as electricity through energy conversion of wastes are currently regarded as highly relevant. Conversion of organic wastes to energy is promising as these technologies can provide green energy to energy scarce agro processing industries.

Energy from biodegradable and non-biodegradable wastes can be recovered through thermal, thermo-chemical and biochemical methods. Considering the organic waste generated in agro-processing plants, biochemical methods, especially biomethanation is suitable. By anaerobic digestion of organic matter a methane rich gas can be produced which is suitable to be burned efficiently for process heat and generate electricity. Anaerobic conversion method can be applied to wastes having high moisture content and is well suited for organic waste waters from food industries and agro processing plants.

Anaerobic digestion is also a waste stabilization method for organic effluents which can reduce the pollutant concentration to an acceptable level so as to be discharged safely. The digestion is done by a group of micro-organisms in the absence of oxygen converting organic matter into methane (60-80%) and carbon dioxide (20-40%). But the problems involved with conventional biogas plants are their inability for fast conversion and the requirement of large digester volumes, especially when dealing with low strength waste waters. The slow operation of digester with long hydraulic retention time of 35 to 40 days makes the digester large. Large digester consumes more construction materials, occupy more space and the installation cost is also high. Anaerobic waste water treatment is more environment friendly method but the above technical problems are restricting the adoption of technology.

Anaerobic digestion of high volume agro-processing effluents is feasible only through high rate bioreactors which can reduce the hydraulic retention time to few days or even hours (James and Kamaraj, 2002). Such a high reduction in hydraulic retention time is favourable for size reduction and cost of digester. High rate anaerobic bioreactors can retain higher concentration of microbial population in the bioreactor and can remove higher level of organic matter. High rate anaerobic treatment is made successful by immobilizing the active biomass in the bioreactor. The cell immobilization with the aid of an inert media enhances the treatment efficiency by longer period retention of biomass within the bioreactor. Up-flow Anaerobic Filter (UAF), Up-flow Anaerobic Sludge Blanket (UASB) Reactor, Anaerobic Fluidized Bed Reactor (AFBR) and Up-flow Anaerobic Hybrid Bio-Reactor (UAHBR) are the common high rate anaerobic bioreactor designs. High rate anaerobic digesters can effectively treat high volume low strength soluble wastes from agro processing industries with maximum biogas production. It has been reported by many workers that the UAHBR design incorporating the concepts of UAF and UASB reactor is advantageous for easy start-up and higher reactor stability (James and Kamaraj, 2003; Bovas and James, 2010; Kumbar, 2016).

1.1 Rubber latex processing

Currently, Kerala is ranked first in India for rubber production with an annual production of 490460 tonnes in 2018-19 (Ministry of Commerce & Industry, 2019). Natural rubber is mainly harvested or derived in the form of a milky colloidal suspension or latex. Latex is collected by making incisions in the bark of the rubber tree. The collected latex mixed with water is coagulated under control conditions using formic acid. The coagulated latex can then be allowed to set in a dish. Once the latex is fully set the excess water is squeezed out by the use of pressing rollers to convert it into a thin sheet. These rubber sheets are then dried by open sun drying or in biomass fired drying chambers.

1.2 Rubber latex processing effluent and its environmental impact

Rubber latex processing plants produce large quantity of effluents which contain wash water, some amount of uncoagulated latex and serum (Mohammadi *et al.,* 2010). Thus, Rubber Latex Processing Effluent (RLPE) contains high amount of degradable organic matter characterised by high TS, BOD and COD. These are biodegradable and results in high oxygen consumption when discharged into water bodies. These effluents are generally not properly treated in many rubber latex plants before discharged to land and often create foul smell (Mohammadi *et al.*, 2010). This will affect the local environment and result in adverse effects on public health. Hence adoption of suitable technology for waste stabilization and energy generation is highly warranted and can be achieved through high rate anaerobic treatment of RLPE.

1.3 Objectives

The present investigation is for studying the energy conversion of RLPE in a high rate anaerobic bioreactor. It was intended to conduct a detailed investigation using a field scale high rate anaerobic bioreactor by installing it in a rubber factory at Anamangad, Malappuram district so as to form guidelines for the design and maintenance of full scale anaerobic bioreactor.

The specific objectives of the study were:

1. To study the biomethanation characteristics of rubber latex processing effluent (RLPE).
2. To study the process parameter for high rate biomethanation of RLPE in a field scale bioreactor.
3. To evolve design criteria for a full scale anaerobic bioreactor for energy production from RLPE.

REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

This chapter presents a review of investigations done by various research workers on characteristics of rubber latex processing effluent, biomethanation of organic effluents, and studies on their treatment using high rate anaerobic bioreactors.

2.1 Biomethanation of wastewater from rubber processing industries

Studies on wastewater from rubber industries in Malaysia were conducted by Mohammadi *et al*. (2010). They opined that conventional treatment facilities were favoured in the past, whereas aerobic, anaerobic and facultative ponds are becoming popular now due to the fact that they are inexpensive and possess high performance even at high organic load. Pollution potential of rubber processing wastes was investigated by Jai *et al*. (2014) and they reported that total dissolved solids, total suspended solids, total solids, ammonia and phosphate were higher than the effluents discharged from other processing industries. BOD and COD values were 1340 and 2834 mg L^{-1}, respectively. An aerobic bio-treatment of rubber processing wastes for 15 days of incubation resulted in BOD and COD reduction of 74.03% and 79.92%, respectively.

Ramanan and Vijayan (2015) treated wastewater from rubber industries with a bacterial consortium for an incubation period of 15 days. This method reduced the TS (79.38%), BOD (73.25%), COD (80.26%) and ammonia (80%) and they opined that exact treatment facilities are needed for proper treatment of effluents according to the standard.

Gamaralalage *et al*. (2016) investigated effectiveness of available treatment facilities in Sri Lankan rubber industries. They reported that many small rubber holding units are releasing wastewater to environment without proper treatment and current treatment facilities have no technology for de-nitrification.

2.2 Biomethanation of food processing and agro-industrial effluents

Cuzin *et al.* (1989) experimented anaerobic digestion of cassava wastes, having high amount of starch, cyanide and low nitrogen in a continuous pilot scale fermenter. They achieved no inhibition with the loading rates of 2.2, 3.6 and 4.2 kg VS m^{-3} d^{-1} and yielded 0.370 m^3 CH_4 kg^{-1} VS.

An anaerobic digestion of tomato processing wastes done by Sarada and Krishna (1989) could get a gas yield of 0.597 m^3 kg^{-1} VS_{added} with a methane content of 72%. Starting up of digestion was achieved by addition of stock for 10-12 weeks.

Albin *et al.* (1990) researched on the biomethanation of solid and semi-solid residues in one and two phase anaerobic digesters. The feed stock comprised of sugar beet leaves from harvesting, sugar beet pulp, remainders from peeling and spent grains from breweries. They opined that this method is applicable to a wide range of residues.

Bazile and Bories (1990) described biogas production and pollution control from sugarcane molasses stillage in a fixed film digester. They found that biogas productivity was in the range 6.8 to 8.4 m^3 m^{-3} d^{-1} with a COD removal of 60-73%.

2.3 Treatment and energy conversion of organic wastewaters using high rate anaerobic bioreactors

High rate anaerobic bioreactors made tremendous changes in industrial wastewater treatment along with energy production (Lettinga, 1984). Calzada *et al* (1984) investigated biogas production from coffee pulp juice in a one and two phase system. One-phase methanogenic digester was operated at 10 day HRT with loading rates 0.5 to 3 g VS $litre^{-1}$ d^{-1}. The two-phase digester was operated with an acidogenic digester and a methanogenic digester. Acidogenic digester worked with loading rates 5.6 g VS $litre^{-1}$ d^{-1} at an HRT of 0.5 day and the methanogenic digester at a loading rate range of 0.6 to 2.4 g VS $litre^{-1}$ d^{-1} at 10 to 5 days. They concluded that the two-phase digester had better performance compared to the single phase system. Acidogenic reactor with 0.5 day HRT coupled with the methanogenic reactor at 8 days HRT exhibited stable operation.

Campos *et al*. (1986) compared the working of an anaerobic filter treating effluent from meat processing industry which had been working for 6 years with broken stones as media at 13 h HRT and a UASB reactor treating vegetable and fruit processing industry wastes. COD removal in anaerobic filter having primary treatment was 80% with organic loading as 1.4 kg of COD m^{-3} d^{-1}. UASB reactor was operated for 255 days and also attained a COD removal of 80%.

Start-up of fluidized beds, anaerobic filters and UASB reactors on two types of pharmaceutical wastes had been compared by Stronach *et al.* (1987). Fluidized beds were operated with glucose, fruit processing, soft drink manufacturing and pharmaceutical wastes. They concluded that pharmaceutical wastes are recalcitrant to anaerobic conversion because they contain substances which are inhibitory to microorganisms but loading up to 7.5 kg COD m^{-3} d^{-1} could be applied with a COD removal efficiency of 78%.

Since then, immobilized cell bioreactor designs were widely used for the treatment and efficient energy production from organic effluents (James and Kamaraj, 2002). They opined that major immobilized reactors include Up-flow anaerobic filter, Up-flow anaerobic sludge blanket reactor, anaerobic fluidized bed reactor and Up-flow anaerobic hybrid reactor.

2.4 Up-flow anaerobic filter

Concept of anaerobic filter was initially developed by Young and McCarty (1969) for waste treatment with a supporting media filled in the reactor. This reactor had the advantage of attachment as well as entrapment of biomass in media allowing very low sludge production.

Tesch *et al.* (1983) concluded that wastewater from sugar refinery could be purified with anaerobic filter having clay support media. They achieved a COD removal of 76% at an HRT of 27 hours with maximum methane production rate of 3.6 m^3 m^{-3} d^{-1}.

Lo *et al.* (1985) treated dairy manure in a fixed film reactor at HRTs 15 to 1 day. They achieved methane contents of 62.1% to 69.3%. They achieved highest volumetric methane production rate of 1.37 litre CH_4 litre^{-1} d^{-1} at 1 day HRT with a loading rate of 52.3 g VS litre^{-1} d^{-1}. Fixed film reactor at 22˚ C with HRT less than 3 days showed more energy production than conventional digesters at 35˚ C and 55˚ C.

Lo and Liao (1986) investigated the ability to adopt different kinds of feed materials and their biodegradation efficiency in a fixed film reactor. The fixed film reactor was operated with a mixture of winery waste and screened dairy manure at an HRT of 4 days. They achieved maximum methane production rate of 8.14 litre CH_4 litre^{-1} d^{-1} at a loading rate of 7.78 g VS litre^{-1} d^{-1}. The corresponding COD and VS reduction efficiencies were 70% and 36%, respectively.

Michael and Freda (1987) compared the anaerobic digestion of cattle slurry in an Up-flow anaerobic filter and a conventional partially stirred digester. They reported methane yields from UAF and conventional digester as 0.18 m^3 kg^{-1} VS_{added} and 0.13 m^3 kg^{-1} VS_{added}. They concluded that UAF was the best due to greater surface area for microbial attachment as well as reduced cost of anaerobic digestion.

An experiment was conducted by Ng and Chin (1987) on an anaerobic filter having randomly packed plastic media for treating piggery wastewater. The wastewater introduced to the filter from its bottom using a timer controlled peristalitic pump. Recirculation flow in filter had successfully removed the bubbles of gas and served to completely mix the influent within the filter. They reported a COD reduction in the range 97% to 83% and VSS reduction of 99% to 90%. Methane content in biogas increased as HRT decreased.

Lo and Liao (1990) compared digestion of baker's yeast wastewater on an anaerobic biological contact reactor (AnRBC) and on a fixed film reactor having PVC as media. Fixed film reactor showed methane gas production rate of 0.46 litre CH_4 litre^{-1} d^{-1} after 4 months of operation.

Marques *et al.* (1990) treated milk factory wastewater in anaerobic filter at HRTs of 24 to 48 hour having PVC pipes as media. They found good performance of filter at loading rates from 0.75 g COD $litre^{-1}$ d^{-1} to 4.5 g COD $litre^{-1}$ d^{-1} with COD reduction in the range of 77% to 93%.

Xavier and Nand (1990) investigated biogas production from cow dung in two digesters with and without media. Digester having media attained maximum biogas of 0.419 m^3 kg^{-1} VS_{added} and methane content of 62% at 30 day HRT.

Prasertsan *et al.* (1994) investigated an anaerobic filter for the treatment of fishery wastewater with HRTs of 36 to 6 days. OLR ranged between 0.3 to 1.8 kg COD m^{-3} d^{-1} for the anaerobic filter operated with PVC rings as media. At 11 day HRT reactor attained 75% COD reduction when operated with an OLR of 1 kg COD m^{-3} d^{-1}. At the same HRT with OLR 1.3 kg COD m^{-3} d^{-1}, the reactor achieved maximum biogas productivity of 1.1 m^3 m^{-3} and 66% COD removal.

Ability of anaerobic fixed film reactor to recover from hydraulic shock loading was studied by Chua *et al*. (1997). The reactor attained 98.1% COD reduction when tested with synthetic wastewater at 5 day HRT. Reactor performance was investigated at HRTs of 2.5, 1.25,1 and 0.5 days with 2, 4, 5 and 10 times hydraulic shock loadings with constant COD loading. At 2, 4, and 5 times shock loadings COD removal, pH and biogas productivity were influenced. The system recovered from this shock loading within 8 days. But at 10 times hydraulic shock loading, the performance of reactor decreased heavily but again at 5 day HRT, the system recovered within few days. The study concluded that this ability of the reactor to recover was due to the immobilized biofilm design.

Acharya *et al.* (2008) treated distillery spent wash in an Up-flow Anaerobic Fixed Film reactor with three different supporting media viz. charcoal, coconut coir and nylon fiber. They reported that reactor with coconut coir as media performed efficiently at 8 day HRT with OLR 23.25 kg COD m^{-3} d^{-1} and attained a COD reduction of 64% with 7.2 m^3 m^{-3} d^{-1} of biogas productivity.

Umana *et al.* (2008) treated dairy manure in two lab scale anaerobic fixed film reactors with different media at HRTs 1 to 5.5 days. Media used in Reactor R1 was a combination of waste tyre rubber and zeolite whereas in reactor R2 it was waste tyre rubber. R1 attained methane yield of 12- 40% higher than R2. They advised optimum HRT for pilot scale fixed film reactor as 4 days.

2.5 Up-flow anaerobic sludge blanket reactor

Lettinga *et al*. (1980) developed a sophisticated anaerobic treatment system using Up-Flow Anaerobic Sludge Blanket reactor for low strength wastes at low HRTs. The reactor had a gas-solid separator at the upper portion. Easy start-up and granulation in the developed reactor was achieved by seeding with granular sludge from existing systems. Granulation is necessary for proper function of UASB reactor and Goodwin *et al.* (1990) suggested that pre-granulation will lead to quick start-up.

Yan *et al.* (1990) investigated treatment of cheesy whey in UASB reactor with influent variation of 4.5 to 38.1 g COD $litre^{-1}$ at HRT of 5 days. They opined that there were two distinct reaction phases, acidogenic and methanogenic. Results revealed that when substrate loading increased, acidogenic region extended throughout the reactor and resulted in failure of the reactor.

Shin *et al*. (1992) operated a two phase UASB reactor for the treatment of distillery wastewater and investigated the efficiencies of both acidogenic and methanogenic UASB reactors. Methanogenic phase was operated effectively at 44 kg COD m^{-3} d^{-1} and attained 80% COD removal with a specific gas production of 16.5 L d^{-1}.

Singh *et al.* (1996) experimented a semi-pilot scale UASB reactor for treatment of a low strength synthetic wastewater at an HRT of 3 hour with OLR 4 kg COD m^{-3} d^{-1}. The reactor attained COD and BOD reductions of 90-92% and 94-96%, respectively with methane production of 141 L kg^{-1} COD.

Buzzini and Pires (2002) treated cellulose pulp mill effluent in UASB reactor and achieved a COD reduction of 80%. Biomass in reactor had good recovering ability under thermal shock loading and acidification. Buzzini and Pires (2007) reported treatment of diluted black liquor from a kraft pulp mill with and without recirculation. Without recirculation the reduction of HRTs from 36 to 30 h did not significantly affect average COD removal.

Saner *et al.* (2014) studied treatment of distillery spent wash in a full scale UASB reactor with a capacity 450 m^3 d^{-1} at 18 day HRT. The reactor achieved COD, BOD and TS reductions of 71.56%, 38.15% and 26.82%, respectively at OLR in the range of 0.93 to 5.03 kg COD m^{-3} d^{-1}. Biogas production was in between 1300-18870 m^3 d^{-1}. Sludge profile in reactor showed a decreasing nature at 6th port from bottom and found to be increased at 7th port.

Daud *et al.* (2018) opined that UASB reactor can successfully be employed for the treatment of industrial and municipal wastes with high COD content in countries having varying temperature conditions. They recommended that UASB reactors can be installed on priority basis in small communities and towns in developing countries.

2.6 Anaerobic fluidized bed reactor

Treatment of wine distillery wastewater in a down-flow anaerobic fluidized bed reactor was studied by Garcia *et al.* (1998). Reactor used ground perlite as carrier with density 213 kg m^{-3} and diameter 0.968 mm. Reactor was operated after 2 months of start-up period. System attained carbon removal efficiency of 75-95% with OLR of 17 kg TOC m^{-3} d^{-1} at HRT 0.35 days.

Synthetic textile wastewater was treated by Sen and Demirer (2003) in a fluidized bed reactor. Reactor took 128 days for start-up with microorganism level 0.06 g VSS g^{-1} of support material. COD and colour reduction in reactor were 60 and 94%, respectively.

Wang *et al.* (2016) investigated two lab scale anaerobic fluidized bed bioreactors for the treatment of primary sludge and thickened waste activated sludge. Primary sludge in reactor achieved 62% and 63% of COD and VSS reductions, respectively when the OLR was 18 kg COD m^{-3} d^{-1} at an HRT of 2.2 days. The thickened waste activated sludge in reactor achieved 56% and 50% COD and VSS reductions, respectively, when operated with an OLR of 12 kg COD m^{-3} d^{-1} at an HRT of 4 days.

Nelson *et al.* (2017) used circulating fluidized bed bioreactor. They reported that mixing and mass transfer of fluidization made it effective to treat municipal and industrial wastewaters. Reactor could treat 90% of influent organic matter and 80% of nitrogen. They concluded that the high efficiency enabled these reactors to treat high organic loads than conventional reactors.

2.7 Anaerobic membrane bioreactor

Anaerobic membrane bioreactor was operated using a membrane for solid-liquid separation. The advantages of membrane bioreactor over conventional treatment methods were increased biomass retention, good effluent quality, less sludge production and more energy production (Lin *et al*., 2013).

Bae *et al.* (2014) compared performance of anaerobic fluidized membrane bioreactor (AFMBR) with that of a staged anaerobic fluidized membrane reactor having anaerobic fluidized bed reactor followed by an AFMBR. Both systems had COD removal reduction in the range of 93 to 96% and they concluded that both system exhibited similar performance. Jensen *et al.* (2015) attained 95% COD reduction while operating an anaerobic membrane bioreactor for the treatment of slaughter house wastewater.

2.8 Anaerobic hybrid reactor

Guiot and Van den Berg (1984) developed the concept of a hybrid bioreactor by hybridizing Up-flow anaerobic sludge blanket reactor and Up-flow anaerobic filter. The reactor had a filter on the upper portion for treating sugar waste at loading rates 5 to 51 g COD $litre^{-1}$ d^{-1}. Upto 26 g COD $litre^{-1}$ d^{-1}, COD reduction was 96% and at higher loading rates conversion reduced greatly.

Kennedy and Guiot (1986) developed a new design combining UAF and UASB by reducing the problem of channelling in UAF and loss of biomass due to floatation in UASB. They concluded that this new design was capable of treating low strength high volume wastes at high organic loading rates and short HRTs.

Calzada *et al.* (1988) developed a two section reactor for methanogenic bioconversion of liquid agro industrial wastes having sludge accumulation at lower part and media in upper part. This reactor could achieve a biogas productivity of 0.44 to 1 litre litre^{-1} at 1.8 day HRT.

Choi *et al* (1989) operated four anaerobic up-flow biofilters (AUBF) with different packing alternatives. They are non packing anaerobic filter (NP-AUBF), two stage up-flow biofilter (2S-AUBF) having packing in top half of the bed, multi stage anaerobic up-flow biofilter (MS-AUBF) having sequence packed and non packed region, and full packed filter (FP-AUBF). COD reduction for all reactors except NP-AUBF was in the range of 89-93% for loading rate of 2-4 kg COD m^{-3} d^{-1}. They reported 2S-AUBF and MS-AUBF performed well in biomass accumulation. They found that 2S-AUBF was cheaper and reduced the problem of channelling and plugging compared to FP-AUBF.

Hong (1990) investigated the performance of a UASB-AF combined reactor and found that the reactor performed best at 4.7 day HRT with a biogas yield of 80 litre d^{-1} having a methane content of 58%. An HRT of 3 day was considered as appropriate for biogas production of 107.3 litre d^{-1}.

Ozturk *et al.* (1993) investigated treatment of dairy effluents in a hybrid reactor with plastic rings as media at HRTs of 0.21 to 0.96 days. The reactor attained COD reduction of 87% at an OLR of 10 kg COD m^{-3} d^{-1}. System tolerated high strength acid whey having OLR of 17 kg COD m^{-3} d^{-1} and attained COD reduction of 75%. It could be concluded that reactor performed good in COD reduction and biomass recovery.

Cordobo *et al*. (1995) compared an anaerobic filter with a hybrid reactor at an OLR of 1 to 8 g COD litre^{-1} d^{-1} and concluded that the hybrid design was effective in removal of organic matter by 92% with a gas productivity of 4.64 L L^{-1}.

Borja *et al.* (1996) studied lab scale hybrid reactor for treating wash water from olive oil mill. Reactor was operated at HRTs of 0.2 to 1.02 days with clay rings as supporting media. They achieved a COD removal of 89% at an OLR of 8 kg COD m^{-3} d^{-1}.

Malaspina *et al.* (1996) experimented anaerobic treatment of cheese whey for developing suitable technologies in disposal problems. The treatment of highly concentrated cheese whey in an Up-flow Hybrid Reactor resulted in a pH drop and caused fast increase in VFA in the reactor. The experiment was continued on two phase combined stirred reactor which had good stability. A new reactor called 'Downflow-Upflow Hybrid' reactor was also developed to attain process stability at high load.

Effect of OLR and biomass on hybrid design was explained by Jianlong *et al*. (2000) and they reported that concentration of attached biomass increase with OLR. Although COD removal was decreasing with increase in OLR, reactor was able to remove more organic matter at higher loading rates.

James and Kamaraj (2002) detailed the design and operation of different anaerobic bioreactors such as up-flow anaerobic filter (UAF), up-flow anaerobic sludge blanket (UASB) reactor, anaerobic fluidized bed reactor (AFBR) and up-flow anaerobic hybrid reactor (UAHR). They reported that UAHR can treat low to high strength effluents at high organic loading rates and low HRT. UAHR was capable of reducing the problem of channelling in UAF and biomass loss by floatation in UASB.

Chaiprasert *et al.* (2003) investigated three hybrid reactors (R1, R2 and R3) with supporting media as nylon fiber with densities 33, 22 and 11 kg m^{-3}. COD removal efficiencies were 87, 84 and 70% in R1, R2 and R3, respectively. They concluded that a decreasing nature in performance was seen with reduction in HRT and the reactor with higher media density was more efficient.

James and Kamaraj (2003) studied Up-Flow Anaerobic Hybrid Reactors supported with coconut shells as well as PVC pall rings as media for the treatment of cassava starch factory effluent at HRTs from 15 to 1 day. A maximum BOD reduction of 99% was observed at the longest HRT. The volumetric gas production increased as HRT was reduced and reached up to 2038 L m^{-3}. The maximum specific gas production was 909 litre kg^{-1} TS_{added} and the CH_4 content of biogas ranged between 64-74%. They concluded that developed up-flow anaerobic hybrid reactor was efficient in pollution control and energy production.

McHugh *et al.* (2006) treated whey waste water in two hybrid reactors (R1 and R2) at psychrophilic temperatures. COD reduction of 70-80% was achieved in R1 at the temperature range of 20-12˚C, whereas 90% reduction was obtained in R2 at the temperature range of 20-14˚C. As temperature reduced to 12˚C in R2, COD removal efficiency decreased due to the disintegration of granular sludge. They concluded that mesophilic temperature of 37˚C was optimum for hybrid design.

Palm oil mill effluent was treated in hybrid reactor at an HRT of 1.5 and 3 days by Najafpur *et al.* (2006). At HRTs of 1.5 and 3 days, the reactor achieved COD reduction of 89% and 97%, respectively. They arrived in a conclusion that flocculated biomass remained in sludge bed due to the effect of packing material and it helped the further development of biomass.

Sunil *et al.* (2007) treated distillery spent wash in laboratory scale anaerobic hybrid reactor and a UASB reactor. They concluded that start-up and granulation was faster in hybrid reactor (45 days) than in UASB (60 days). Optimum HRT was 5 days with an organic loading rate 8.7 kg COD m^{-3} d^{-1} and COD reduction was 79% and 74.5% in hybrid and UASB reactors, respectively.

Araujo *et al.* (2008) treated wastewater from household and personal products industry in a hybrid reactor with coconut shell as media at HRTs of 60, 50 and 40 hour and attained COD reductions of 80%, 77% and 72%, respectively.

Bovas (2009) experimented on batch anaerobic digestion and semi-continuous digestion of rice mill effluent with the intention of testing media compatibility in hybrid reactor. Lab scale Up-flow anaerobic hybrid reactors were developed and found that rubber seed outer shell was more suitable than polyurethane due to the favourable microstructure available for biomass attachment.

James and Kamaraj (2009) treated cassava starch factory effluent in Up-flow anaerobic hybrid reactors to assess the pollution control and energy production. Reactors had been operated with two different media as coconut shell and PVC pall rings. Maximum specific gas production obtained in reactor 1 and reactor 2 at 15 day HRT were 1108 and 1030 litre kg^{-1} VS, respectively. They achieved maximum BOD and COD reductions of 99% and 96.2%, respectively in two reactors and concluded that reactor with coconut shell was better than that with PVC pall rings.

Gonclaves *et al.* (2012) investigated performance of hybrid digesters for treating olive mill effluent (OME) in combination with piggery effluent. Digesters were fed with 8% to 83% volume fraction of olive mill effluent (OME). Digester achieved biogas production of 3.16 m^3 m^{-3} d^{-1} at a highest volume fraction and an OLR of 7.1 kg COD m^{-3} d^{-1}. The study revealed that digester recovered from shock loading and was capable to reduce the loss of biomass.

Kundu *et al*. (2012) studied the operating temperature and microbial population in hybrid reactors. Reactors were operated at temperature 37, 45 and 55˚C at OLR of 2.22 kg COD m^{-3} d^{-1} and they reported that 37˚C was the best temperature for microbial community.

Li *et al.* (2012) investigated the COD removal performance of hybrid reactors at low temperature (4˚C) and room (25˚C) temperature. They found COD removal efficiency increased gradually over time from 39.76% to 66.27% for low temperature hybrid bioreactor and fluctuated between 81.85% and 94.78% for room temperature hybrid bioreactor. They observed good microbial activity even at lower temperature.

Narra *et al.* (2014) compared performance of hybrid reactors with 4 different media such as gravel, pumice stone, polypropylene saddles and ceramic saddles at HRTs of 3 to 15 days. The study could reach the conclusion that reactor with pumice stone at 15 day HRT had maximum COD reduction and methane yield.

Wahab *et al.* (2014) had operated a hybrid reactor with lignocellulosic biomass as media. Acclimation of biomass and start-up of reactor was obtained in one month and reached an OLR of 25 g COD litre^{-1} d^{-1}. After 3 months of non-feeding period reactor could restart within 15 days. They concluded that by using lignocellulosic materials as media, reactor could restart after inactive periods also.

Kumbar (2016) investigated full scale and experimental Up-flow anaerobic hybrid bioreactors for energy production from waste coconut water with coconut shell as media. Experimental reactor had specific biogas production of 225.73 litre kg^{-1} TS_{added} at 15 day HRT with TS and BOD reduction of 80.97% and 91.56%, respectively. For maximum energy production high HRT was preferred and for better daily biogas production short HRT was recommended to be adopted.

Akbar *et al.* (2017) studied the role of internal packing in hybrid design for treatment of palm oil mill effluent. They opined that in hybrid design, immobilized biomass in upper layer contributed treatment of effluent at low up-flow velocities.

Kavimani *et al.* (2019) treated organic wastewater with COD higher than 3000 mg L^{-1} in a hybrid reactor at HRT of 24 hour. The system attained stability at an effluent pH 7.9 with a COD removal of 87.9%.

2.9 Process parameters of high rate reactors

Development of high rate reactor depends on many factors such as media, hydraulic retention time, start-up of reactor etc. Reviews of research on these factors are relevant in the proper development and operation of up-flow anaerobic hybrid reactor to treat rubber latex processing effluent.

2.9.1 Media characteristics

Nordstedt and Thomas (1985) inspected properness of wood blocks as media and no degradation was observed after one year due to the high lignin content in wood block.

The studies by Albagnae (1990) on biomass retention in anaerobic reactors revealed that in reactors with non porous media, biomass retention was dependent on media shape and void space and it lead to development of sludge with good settling characteristics.

Andreoni *et al.* (1990) conducted studies on two anaerobic fixed bed up-flow reactors treating wastes from wood pyrolysis. Reactors were operated with wood chips and PVC as media. Wastes contained pyrolignitic acids and was treated in combination with swine slurry. At 10% (v/v) concentration the reactor with wood chips media showed resistance to pyrolignitic acids.

Porous cuboids phenol resin in the size of 2 cm^3 with porosity from 90 to 95% were used in an UASB-AF reactor by Hong (1990) and observed better methane recovery at 4.7 day HRT.

Young (1991) reported that media need to be placed in the two-third portion of reactor. He reviewed that media helped in gas-solid separation, improved the uniform flow through reactor and the contact of biomass with raw effluent constituents in the reactor.

James and Kamaraj (2009) studied the immobilization of biomass on coconut shell and PVC pall rings in the treatment of cassava starch effluent in an up-flow anaerobic hybrid reactor. Reactor with coconut shell as media performed well due to the favourable surface configuration for microbial attachment and media cost could be reduced by 1-2% for coconut shell compared to synthetic media.

2.9.2 Hydraulic Retention time

Tesch *et al.* (1983) conducted treatment of wastewater from sugar refinery in an anaerobic filter and concluded that as HRT decreased, fermentation increased than methanogensis because of the relative changes in the microbial population.

Yang *et al.* (1992) conducted a study in fixed bed reactor with polyacrylate as media on a saddle shaped slag support for the treatment of synthetic wastewater of glucose and corn steep-liquor. They achieved good methane production and COD reduction of 85% at HRT of 8 hour and revealed that at short HRT, immobilized cell reactor performed well.

James and Kamaraj (2009) found that pollutant reduction in UAHR decreased with reduction of HRTs from 15 to 1 day.

2.9.3 Start-up of high rate anaerobic reactors

Tesch *et al.* (1983) studied anaerobic filter for treatment of sugar refinery along with sludge from municipal sewage and found that this helped in start-up of the reactor in a few days.

Start-up and granulation phase study done by Sunil *et al*. (2007) revealed that hybrid and UASB reactors achieved pseudo-steady state in 45 and 60 days, respectively. Granules with black colour and spherical shape appeared first in hybrid reactor than in UASB reactor. In pseudo-steady state, the reactors achieved constant pH and better COD removal efficiency.

2.9.4 Other process parameters

Nordstedt and Thomas (1985) investigated digestion of whey and cellulose with media as wood chip and plastic and reported that through pH control, reactors were able to produce methane at the rate of 0.17 litre g^{-1} VS added.

Campos *et al*. (1986) recommended that average vertical velocity in an anaerobic sludge blanket reactor should be 0.7 m $hour^{-1}$ and pH adjustment should be done before treatment.

James and Kamaraj (2003) treated cassava starch factory effluent in up-flow anaerobic hybrid reactor with pH ranges 4.7 to 5.3. The treated effluent had above neutral pH ranging from 6.8 to 7.4 and this indicated the stable operation of UAHR.

MATERIALS AND METHODS

CHAPTER III

MATERIALS AND METHODS

The procedure adopted for analysis of the characteristics of rubber latex processing effluent (RLPE), methodology for batch anaerobic digestion study and the assessment of field scale high rate bioreactors are elucidated in this chapter. Methodology for evolving design criteria for a full scale anaerobic high rate bioreactor for energy production from RLPE also is discussed here.

3.1 Physico-chemical characteristics of RLPE

Analysis of the physico-chemical characteristics of the substrate is relevant in the design and operation of high rate anaerobic bioreactors.

3.1.1 Total solids (TS)

Amount of solids present in a known volume of sample is known as Total Solids. Total solids include total suspended solids and total dissolved solids.

Procedure for determination of TS was adopted from American Public Health Association (APHA, 2017). A known sample was evaporated in a weighed dish and dried in a drying oven. Evaporated sample was then dried in an oven for 1 hour at 103 to 105˚C. The dish was cooled in a desiccator and weighed. The process of drying, cooling and weighing was repeated to get concordant weight. Then TS was calculated as:

$$\text{Total solids (mg L}^{-1}\text{)} = \frac{(A - B) \times 1000}{\text{Sample volume, mL}}$$

Where,

A = Weight of dried residue + dish, mg

B = Weight of dish, mg

3.1.2 Volatile solids (VS)

Weight loss on ignition of the residue of total solids for a specific time at specific temperature is termed as Volatile Solids. Procedure to determine VS was adopted from American Public Health Association (APHA, 2017).

The residue from total solids was ignited in a muffle furnace at 550 ˚C for 15 to 20 minutes. The dish was cooled to dissipate the heat. The dish was placed in a desiccator for final cooling. The process of igniting, desiccating and weighing was repeated until constant values were obtained.

$$\text{Volatile solids (mg L}^{-1}\text{)} = \frac{(A - B) \times 1000}{\text{Sample volume, mL}}$$

Where,

A = Weight of residue + dish before ignition, mg

B = Weight of residue + dish or filter after ignition, mg

3.1.3 Biochemical oxygen demand (BOD)

Biochemical oxygen demand is the amount of dissolved oxygen needed for the aerobic microorganisms to decompose or breakdown the organic matter in a water sample at a specific temperature over a specific period.

Five day BOD test was conducted at 20˚C by the standard procedure (APHA, 2017). The diluted sample was incubated in a 300 mL BOD bottle for 5 days at 20˚C in a BOD incubator (Fig. 3.1). Dilution water was prepared by adding 1 mL each of phosphate buffer, $MgSO_4$ solution, $CaCl_2$ solution and $FeCl_3$ solution. Dissolved oxygen was computed before and after incubation and BOD_5 was calculated as:

$$BOD_5\ (mg\ L^{-1}) = \frac{D_0 - D_5}{P}$$

Where,

BOD_5 = Five day biochemical oxygen demand, mg L^{-1}

D_0 = DO of diluted sample immediately after preparation, mg L^{-1}

D_5 = DO of diluted sample after 5 days incubation at 20ºC, mg L^{-1}

P = Decimal volumetric fraction of sample used.

Fig. 3.1 BOD incubator

3.1.4 Chemical oxygen demand (COD)

Chemical oxygen demand is the amount of dissolved oxygen needed to decompose organic and inorganic matter in water sample. COD level in water sample are always higher than BOD levels.

An open reflux method was conducted by the standard procedure (APHA, 2017). Blended water sample of 50 mL was taken in a 500 mL refluxing flask. Then 1 g of $HgSO_4$, 5 mL of H_2SO_4 and 25 mL of $K_2Cr_2O_7$ were added to the flask and mixed the contents. The flask was then attached to the condenser and refluxed for 2 hour. The contents were then cooled to room temperature and titrated with ferrous ammonium sulphate (FAS), using 2 to 3 drops of ferroin indicator. A blank was also run. COD was calculated as:

$$\text{COD (mg L}^{-1}\text{)} = \frac{(A-B) \times M \times 8000}{\text{Sample volume, mL}}$$

Where,

A = FAS used for blank, mL

B = FAS used for sample, mL

M = Molarity of FAS,

3.1.5 pH value

pH is the negative logarithm of hydrogen ion concentration in a solution. pH of samples were analysed using electrometric method (APHA, 2017). A Digital pH meter MK-VI with a pH range of 0-14 pH and 0.01 resolution was used (Fig. 3.2).

Fig. 3.2 pH meter

3.1.6 Gas measurement

Volume of daily biogas production from bioreactors was measured using Insref make wet type gas flow meters (Fig. 3.3). Specifications of flow meters are shown in Table 3.1.

Fig. 3.3 Wet type gas flow meter

Table 3.1 Specification of wet type gas flow meters

Model	Insref IRI 08	Insref IRI 06
Capacity/Revolution	1 litre	3 litre
Graduation	0.01	0.01
Minimum flow rate	30 L h^{-1}	90 L h^{-1}
Maximum flow rate	270 L h^{-1}	810 L h^{-1}
Accuracy	±0.5% of full scale in all models	
Pressure gauge	5.08 cm water gauge to 30.48 cm water gauge	
Connections	For upto 1.27 cm ID flexible piping	

3.1.7 Methane content

Methane content in biogas was determined using a sacharometer (Fig. 3.4). A known quantity of biogas was passed through the saturated KOH solution in the sacharometer. Methane gets collected at top of the sacharometer and CO_2 is absorbed by the saturated KOH solution. Methane content was computed as follows:

$$\text{Methane content, \%} = \frac{\text{Volume of gas collected at the top of sacharometer} \times 100}{\text{Total volume of gas injected}}$$

Fig. 3.4 Sacharometer

3.2 Terminologies related to gas production

Different terminologies used to describe gas production from bioreactors are as below:

Daily biogas production : Total gas produced in litres per day, L d^{-1}

Volumetric biogas production : Total gas production per unit volume of digester, L m^{-3}

Specific gas production : Total gas production in litres per kg Total Solids added, L kg^{-1} TS_{added}

Biogas productivity : Total gas production in litres per litre of feed, L L^{-1}

3.3 Operational and Performance parameters of bioreactors

Various operational parameters need to be defined in the investigations on anaerobic bioreactors. The performance parameters are used for the assessment as indicators.

3.3.1 Hydraulic retention time

Time period for which the substrate stays in the digester/reactor to produce biogas is called hydraulic retention time (in days). It is the ratio of the volume of digester to the volume of daily feed material.

3.3.2 Loading rates

The capacity of high rate anaerobic systems are assessed based on loading rates as given below:

$$\text{Hydraulic loading rate (HLR), L m}^{-3} = \frac{\text{Volume of feed, litre}}{\text{Reactor volume, m}^3}$$

$$\text{TS loading rate, kg m}^{-3}\text{ d}^{-1} = \frac{\text{kg TS per litre} \times \text{Volume of feed (L d}^{-1}\text{)}}{\text{Reactor volume, m}^3}$$

$$\text{BOD loading rate, kg m}^{-3}\text{ d}^{-1} = \frac{\text{kg BOD per litre} \times \text{Volume of feed (L d}^{-1}\text{)}}{\text{Reactor volume, m}^3}$$

3.3 Batch anaerobic digestion study

In order to understand the biomethanation characteristics and possibilities for anaerobic digestion of RLPE, a batch anaerobic digestion study was conducted (Fig. 3.5). To obtain the daily gas production from experimental digesters water displacement method was adopted. Five litre capacity plastic digesters were connected with 3 litre capacity graduated cylinders used as water displacement meters for the experiment (Fig. 3.6). 4 treatments with 3 replications were used. Cow dung was used as inoculum for the first 3 treatments where as effluent collected from a conventional biogas plant was used for the 4th treatment. Daily biogas production was measured for 75 days. The pH values and TS were noted before and after digestion. There were 4 treatments replicated thrice for the experiment and are shown below:

4 treatments were:

T0 – Inoculum : water (1:1)

T1 – Inoculum : RLPE (1.1)

T2 – Inoculum : water : RLPE (1:1:2)

T3 – Effluent from conventional biogas plant: RLPE (1:1)

Fig. 3.5 Experimental set up for batch anaerobic digestion

Fig. 3.6 Arrangement of experimental digesters for batch anaerobic digestion

3.4 Installation and set-up of field scale Up-flow Anaerobic Hybrid Bioreactors

The configuration selected for field scale high rate anaerobic bioreactors were Up-flow Anaerobic Hybrid Bioreactors (UAHBR) based on the previous studies conducted (James and Kamaraj, 2009; Bovas and James 2010; Kumbar, 2016). Two field scale UAHBRs were installed at a rubber latex processing plant at Anamangad, Malappuram district, Kerala. Rubber latex processing effluent from the plant was used to feed the bioreactors.

3.4.1 Configuration of UAHBR

The basic units of field scale UAHBRs available at KCAET Tavanur were reconditioned for installation at the experimental site (Fig. 3.7). The bioreactors were fabricated with 30.5 cm diameter PVC pipes with a total volume of 148.2 litres and a liquid volume of 130 litres. Upper 37.93% of reactor height was filled with broken pieces of coconut shell as media with a porosity of 67.56 % and bulk density 410.95 kg m^{-3}.

An effluent outlet and gas outlet with gas flow meters were provided in the reactor. The dimensions of UAHBR are:

Diameter of reactor	: 30.5 cm
Height of reactor	: 203 cm
Media height of reactor	: 77 cm
Height above media filled portion	: 20 cm

3.4.2 Automatic feeding and photo capturing

The field scale UAHBRs were set-up with automatic feeding and photo capturing technique for measuring daily gas production from the reactor. The experimental UAHBR system included a diaphragm pumps, a digital electronic timer switch, Raspberry Pi, Raspberry Pi camera module, Jio modem, Battery and SMPS as shown in the line diagram (Fig. 3.8).

Fig. 3.7 Pilot scale UAHBR installed at rubber latex processing unit

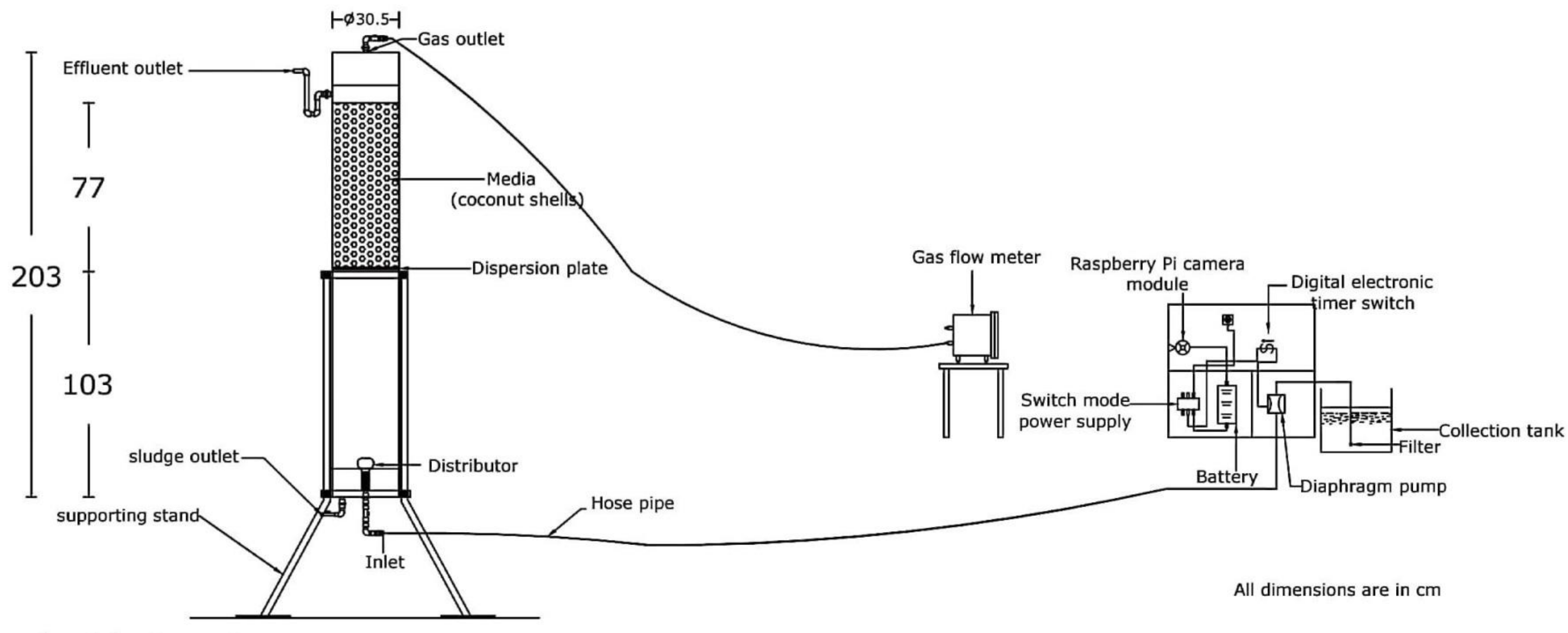

Fig. 3.8 Line diagram of UAHBR set-up

The system had two parts (Fig. 3.9); the automatic feeding system and the monitoring system. The main part of the automatic feeding system consisted of two diaphragm pumps which were provided to feed the RLPE to both bioreactors. Both pumps were connected to a programmable timer. The diaphragm pumps started and fed the predetermined quantity of RLPE to the bioreactors at the programmed time.

The second part was the monitoring system which was used for getting the gas flow meter reading transmitted. The capturing of image of the gas flow meter counter was achieved using a raspberry Pi camera module. The programmed raspberry Pi could send the captured image to a designated email ID through a Wi-Fi connection provided in the system. The Camera module was programmed to capture the image at the predetermined time. A 12V lead acid battery of 8 Ah capacity was used to power the system.

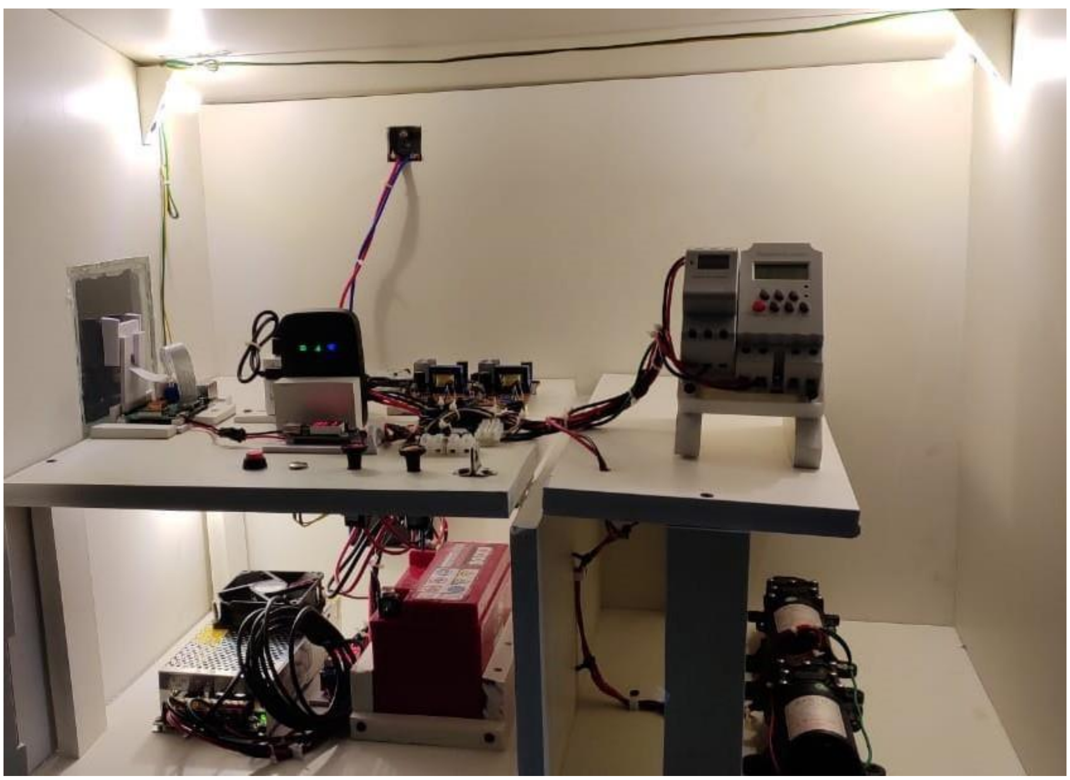

Fig. 3.9 System for automatic feeding and image capturing

3.4.2.1 Diaphragm pumps and digital electronic timer switch

Two diaphragm pumps which can work on 12V, 3A direct current (Fig. 3.10) with a flow rate of 4 L min^{-1} were provided to feed the RLPE to the bioreactors. Pumps were connected to a DC digital electronic timer switch (Fig.3.11) which automatically switched on and switched off the pumps at predetermined times.

Fig. 3.10 Diaphragm pumps

Fig. 3.11 Digital electronic timer switch

3.4.2.2 Raspberry Pi, Switch Mode Power Supply (SMPS) and battery

Raspberry Pi 3 Model B had 1 GB RAM, Wi-Fi, Bluetooth and 40 GPIO Pin. Raspberry Pi camera module was capable of capturing images and was controlled by the program.

The SMPS had AC input range of 110 to 220V and a DC output of 12V at a current rating of 10A. DC power from SMPS was stored by the rechargeable battery (12V, 8 Ah). The system was provided with a 5V, 2 A Step-Down buck converter module so that Raspberry Pi will work on that voltage-current range.

3.4.3 Feed inlet

Feed inlet was provided with PVC pipe of 20 mm diameter and was connected to reactor at bottom through a non-return valve. The reactor was provided with a distributor at the bottom which helped proper distribution of the influent and was helpful in avoiding any blockage or channelling by sludge accumulation at the base. The inlet pipe was connected to the outlet of the automatic feeding pump through a 6mm flexible plastic hose.

3.4.4 Effluent outlet and Sludge outlet

Effluent outlet made of 20 mm diameter PVC pipe was placed above the top level of media. In order to prevent escape of gas, effluent outlet had a ‘U’ shaped configuration. The sludge outlet was provided at the bottom of the reactor using 20 mm diameter PVC pipe.

3.4.5 Gas outlet

At the top of the reactor cap a gas outlet was provided with 20 mm diameter PVC pipe through a PVC ball valve. Gas outlet was connected to the wet gas flow meters through hose pipes having 15 mm diameter flexible plastic hoses.

3.4.6 Performance evaluation of UAHBR

The anaerobic hybrid reactors were started up using filtered cow dung slurry mixed with water in the ratio 3:1. After observing stable daily gas production and pH, UAHBRs were started up by feeding 12 L d^{-1} of RLPE. The start-up daily feed was 12 litres corresponding to 10 day HRT. The biomass content in reactor was expected to reach a pseudo-steady state (James and Kamaraj, 2009) and likely to remain at that state after prolonged operation. The biogas production and pH were monitored to assess attainment of pseudo-steady state. At that stage the TS and BOD of effluent from bioreactors were observed. The reactors were then operated at different HRTs by increasing the loading rates progressively. The UAHBR was thus operated at 10, 7, 5, 3 and 2 day HRTs.

3.4.7 Design criteria for full scale anaerobic bioreactor

A design criterion for a full scale anaerobic bioreactor to treat RLPE was evolved based on the study in the field scale bioreactor. Maximum possible effluent discharge from the rubber latex processing plant and the possible operating parameters were assessed for the purpose. Quantity of coconut shell required in reactor was quantified. Optimum HRT and gas production obtained in UAHBR was regarded as key factors for designing full scale reactor.

RESULT S AND DISCUSSION

Chapter IV

RESULTS AND DISCUSSION

The results of the investigations on the characteristics of rubber latex processing effluent (RLPE), batch anaerobic digestion of RLPE, performance evaluation of field scale Up-flow anaerobic hybrid bioreactors and the evolution of design criteria for a full scale anaerobic bioreactor for energy production from RLPE are presented and discussed here.

4.1 Physico-chemical characteristics of RLPE

The results of the analyses done for various physico-chemical characteristics of RLPE samples are given in Table 4.1. RLPE was a very dilute waste water with TS and BOD, in the ranges of 9281.4-12892.1 mg L^{-1} and 2040.3-3105.5 mg L^{-1}, respectively. The pH was in the acidic range and was observed to vary in the range 5.1-6.1 during the period of investigation. These results are comparable with the values obtained by Ramanan and Vijayan (2015). They reported TS of 9700 mg L^{-1}, BOD of 4300 mg L^{-1} and a pH of 5.7 ± 0.30 for RLPE. The Volatile Solid content was found to be 2356 mg L^{-1} and this value was also similar to the reported value of 1845 mg L^{-1} by Jacob (1994) for rubber sheet processing effluent. Bovas (2009) reported a BOD of 3599 mg L^{-1} and TS of 3090 mg L^{-1} for rice mill effluent.

COD of RLPE was observed to be 5856 mg L^{-1} and was higher than rice mill effluent. BOD: COD ratio of 0.44 obtained in this study showed good biodegradability. Jacob (1994) also reported that rubber effluents having physico-chemical characteristics in these range showed good biodegradability. Bovas (2009) observed a BOD: COD ratio of 0.88 for rice mill effluent, whereas James and Kamaraj (2009) reported a ratio of 0.57 for sago factory effluent, in both cases good biodegradability was achieved by them.

Table 4.1 Characteristics of RLPE

Sl. No.	Parameters	Mean value
1	Total solids, mg L^{-1}	11086.7
2	Volatile solids, mg L^{-1}	2356
3	Biochemical Oxygen Demand, mg L^{-1}	2572.9
4	Chemical Oxygen Demand, mg L^{-1}	5856
5	pH	5.6
6	BOD : COD ratio	0.44

4.2 Batch anaerobic digestion of RLPE

Most organic effluents are easily biodegraded. Possibilities for biodegradation of RLPE were important to evolve a proper anaerobic treatment protocol for anaerobic digestion in a high rate bioreactor. Atagna *et al.* (1999) reported that RLPE had the ability to support microbial population. Thus a batch anaerobic digestion study was taken up as a preliminary experiment to investigate the biomethanation characteristics of RLPE.

Table 4.2 Parameters of batch digestion study

Sl. No.	Treatments	Total solids (TS), mg L^{-1}		TS Reduction (%)	pH	
		Initial	Final		Initial	Final
1	T0	27382	11920	56.46	7	8.1
2	T1	15520	6600	57.47	6.7	7.8
3	T2	19524	9550	51.08	6.9	7.8
4	T3	6527	4527	30.63	7	8.2

From Table 4.2 it can be seen that T0, the control treatment exhibited a TS reduction of 56.46%. T1 and T2 obtained similar TS reductions of 57.47 and 51.08 per cent respectively. Bovas (2009) observed 60.2% TS reduction for a batch digestion study of rice mill effluent which was conducted for a duration of 135 days. TS reduction in T3 was 30.63 % which was lower than other treatments. The result from T3 showed that the inoculum used in T3 was inferior to ordinary cow dung slurry to be used as inoculum. The pH in all treatments was observed to be raised at the end of digestion. The final pH of all the treatments reached the values in the range 7.8-8.2. A similar trend was observed by Ramanan and Vijayan (2015) also.

Daily biogas production of different treatments is shown in Fig. 4.1

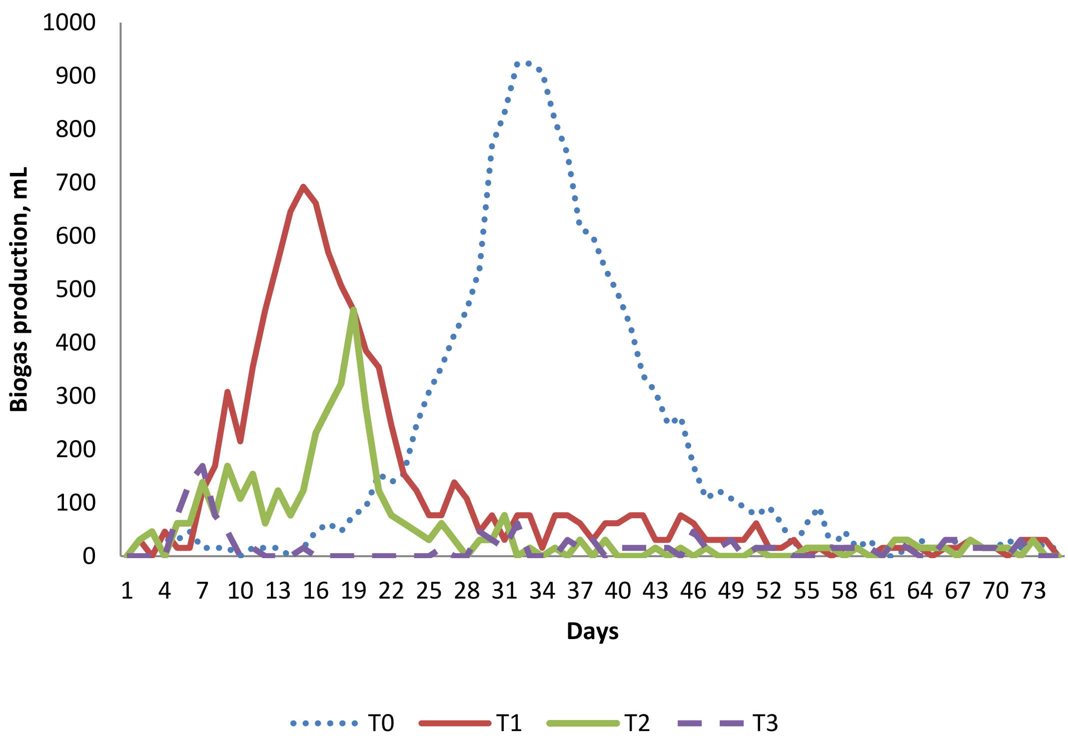

Fig. 4.1 Daily biogas production in batch anaerobic digestion study

From Fig 4.1 it can be seen that T0 had slow gas production in the beginning and picked up gas production after two weeks. The peak gas production of 923 mL occurred on 32nd day and started declining after 34th day. Up to 49th day gas production was good, later biogas production reduced to below 100 mL. Treatment T3, inoculated with effluent from biogas plant did not exhibit gas production after the first week and the daily gas production remained very low throughout the remaining period of the experiment which lasted for 75 days. Treatment T1, mixture of cow dung and RLPE (1:1), showed maximum gas production of 690 mL on 15th day and declined to below 100 ml after 24th day. T2, mixture of cow dung, water and RLPE (1:1:2), obtained peak gas production of 460 mL on 19th day and rapidly declined to very low levels. During the study both T1 and T2 showed maximum gas production within 3 weeks and thereafter decreased. The treatment T3, combination of effluent from an existing biogas plant as inoculum and RLPE obtained 160 mL of daily gas production on 8th day which was the maximum daily gas production in T3. Even at different inoculum ratio a substantial amount of biogas was generated. The difference in biogas production was due to the difference in solid contents of different treatments. Gas production in T0, T1 and T2 were higher compared to T3 which indicated that effluent was inferior to cow dung to be used as inoculum. The biodegradability rate of T0 and T1 were different as RLPE had more soluble organics whereas cow dung had more insoluble/partially soluble compounds. This was the reason for difference observed in the biomethanation characteristics between different treatments. The results showed highest biogas production in T0 as this treatment had maximum TS content followed by T1 and T2.

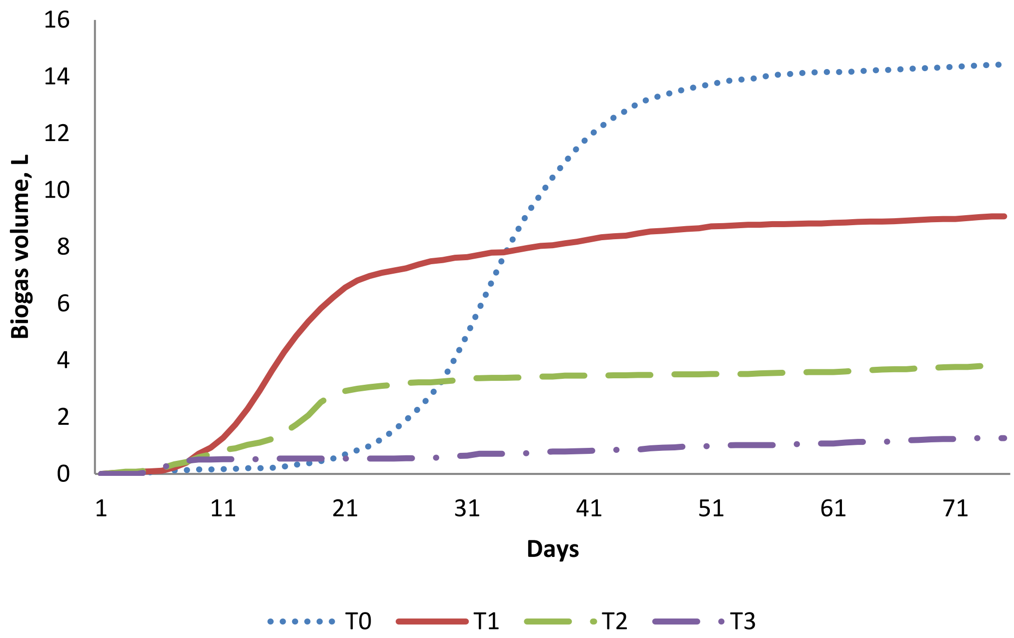

Fig. 4.2 Cumulative biogas production in batch study

The cumulative biogas production from different treatments is shown in Fig. 4.2. The control treatment had more cumulative biogas production of 14.43 L. Total gas production in T1, T2 and T3 are 9.07 L, 3.80 L and 1.26 L respectively (Fig. 4.2). Biogas productivity of 3.60, 2.26, 0.95 and 0.315 L L^{-1} was achieved for the treatments T0, T1, T2 and T3 respectively. These differences in cumulative biogas production were due to the difference of total solids in the treatments. RLPE had more soluble contents and cow dung contained more partially soluble and insoluble compounds. Control treatment (T0) had higher solids contents than others. Difference in T0, T2 and T3 was due to the differences in the ratio of RLPE and cow dung.

In all treatments, RLPE showed good biodegradability. This study concluded that RLPE could be subjected to biomethanation and cow dung can be used as inoculum. Even at a lower inoculum ratio the system could be started up yielding substantial amount of biogas coupled with good TS reduction. Treatment T3 proved that if effluent from an existing biogas plant for RLPE is used as inoculum, it should be ascertained that the system is functional with active microbial population.

4.3 Operation and performance of pilot scale up-flow anaerobic hybrid bioreactor

Performance of two identical UAHBRs installed at the rubber latex processing factory at Anamangad, Malappuram were assessed by operating them at varying HRTs. Wastewater drained from the factory was collected in an effluent tank. This raw effluent was fed into the reactor through the reactor feeding system. The bioreactors were started up by feeding cow dung slurry mixed water and the microbial activity was observed by monitoring gas production. Subsequently, semi continuous feeding of RLPE was commenced with 12 litres per day corresponding to 10 day HRT. The bioreactors were operated at 10, 7, 5, 3 and 2 day HRT. Altering of HRT was done when reactors attained pseudo-steady state (PSS) at a particular HRT. During the study an interruption of 2 months in operation occurred due to shut down of the processing unit due to Covid 19.

4.3.1 Performance of UAHBR at 10 day HRT

Reactors were operated for 40 days at 10 day HRT for stabilisation and the pH, TS and BOD of the influent and effluent were measured. The variation of pH of influent and effluent along with the variation of daily biogas production is shown in Fig. 4.3. pH of influent RLPE during the period ranged from 5.3 to 6. These pH values were higher than the pH values observed by James and Kamaraj (2003) for cassava starch factory effluent. It appeared that fresh RLPE was less acidic than other fermented organic wastewaters from food processing plants like cassava starch factory effluent and rice mill effluent (Bovas and James, 2010). The treated effluent from bioreactors achieved pH values of 7.2 to 7.3 and reached 7.6 towards the end of the 10 day HRT period. Since the effluent pH remained above neutral it indicated the stability of bioreactors to treat RLPE. A similar trend was also observed by James and Kamaraj (2009) for cassava starch factory effluent. Methane content of biogas was 66 %. Timur and Ozturk (1999) reported methane content in the range of 58 to 75 per cent, in the anaerobic treatment of land fill leachate.

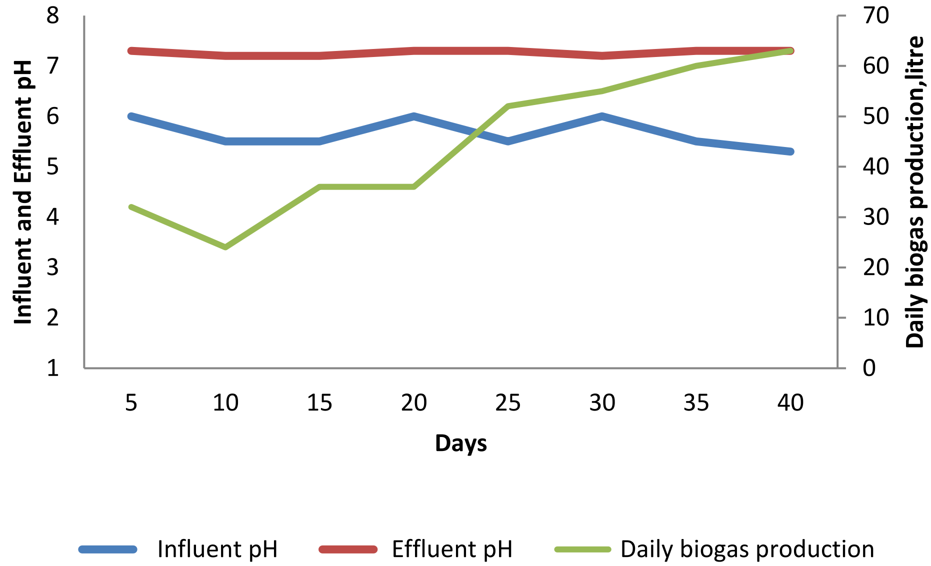

Fig. 4.3 Variation of pH and daily biogas production at 10 day HRT period

Table 4.3 Process parameters of UAHBR at 10 day HRT period

Week	pH (weekly mean)		Daily biogas production*, L	Biogas productivity, L L^{-1}
	Influent	Effluent		
1	6	7.2	26.61	2.21
2	5.5	7.3	31.00	2.58
3	5.3	7.3	49.14	4.09
4	5.3	7.6	63.00	5.25

*Weekly mean

Gas production is the key indicator for the performance of UAHBRs. Bioreactor attained the pseudo-steady state at 4th week and achieved 63 litres of daily biogas production with an effluent pH of 7.6 (Table 4.3). This indicated good methanogenic activity in the bioreactor during the 10 day HRT period. Biogas productivity of 5.25 L L^{-1} obtained on 40th day also showed a good sign of the performance.

Table 4.4 TS and BOD reduction at 10 day HRT period

Week	TS, mg L^{-1}		TS reduction, %	BOD, mg L^{-1}		BOD reduction,%
	Influent	Effluent		Influent	Effluent	
1	9712.50	2150.00	77.80	2062.50	600.46	70.88
2	12340.17	2497.50	79.76	2700.00	600.00	75.50

The TS reduction of 79.76% achieved (Table 4.4) at 10 day HRT is further proof for the enhanced microbial activity. TS reduction obtained in this study is higher than that reported by Kumbar (2016) for waste coconut water (62.51%). Ramanan and Vijayan (2015) observed 79.38% of TS reduction for waste water from natural rubber processing plant using bacterial consortium. The BOD reduction was 75.50% (Table 4.4.) which was much lower than the reduction of 98.6% observed for cassava starch factory effluent by James and Kamaraj (2003). Reactor showed high TS and BOD reduction at this HRT and indicated that high pollutant reduction is possible in this long HRT.

4.3.2 Performance of UAHBR at 7 day HRT

Performance of UAHBR in terms of influent and effluent pH, daily biogas production and TS and BOD reductions were observed during the 7 day HRT period. Influent pH did not affect reactor performance and effluent pH remained above neutral throughout (Fig 4.4). During the start of 7 day HRT period the biogas production from the bioreactor got slightly reduced due to the change in HRT. With passing of time bioreactor stabilised as indicated by the effluent pH and daily biogas production. Methanogenic activity increased at the 3rd week of operation at 7 day HRT with a maximum daily biogas production of 95 litres (Table 4.5). The biogas productivity of

5.27 L L^{-1} indicated that there is not much difference in the conversion of solids to biogas compared to 10 Day HRT period.

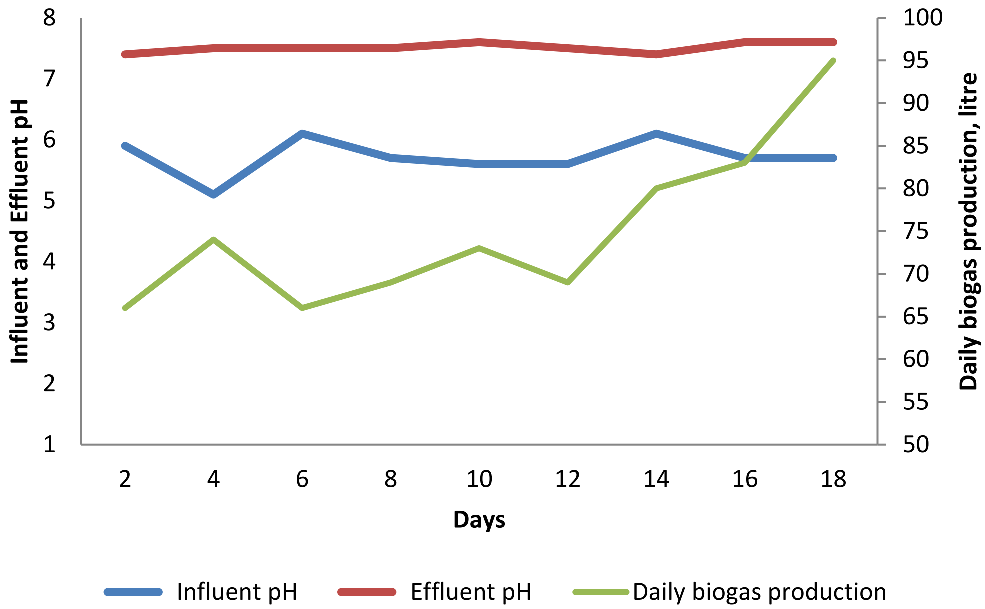

Fig. 4.4 Variation of pH and daily biogas production at 7 day HRT period

Table 4.5 Process parameters of UAHBR at 7 day HRT period

Week	pH (weekly mean)		Daily biogas production*, L	Biogas productivity, L L^{-1}
	Influent	Effluent		
1	5.70	7.46	62.42	3.46
2	5.63	7.53	72.14	4.00
3	5.90	7.50	95.00	5.27

*Weekly mean

Table 4.6 TS and BOD reduction at 7 day HRT period

Week	TS, mg L^{-1}		TS reduction,%	BOD, mg L^{-1}		BOD reduction,%
	Influent	Effluent		Influent	Effluent	
1	11634.14	4466.00	61.6	3056.5	1200.00	60.07
2	12892.15	3512.19	71.24	3105.56	826.84	73.37

TS and BOD reductions of 71.24 % and 73.37 % were obtained at the end of 7 day HRT period (Table 4.6). By comparing the performances in first and second weeks, bioreactor gained 10 per cent increase in both TS and BOD reduction in the second week. Compared with 10 day HRT, the bioreactors showed a nominal decrease in pollutant reduction. Chaiprasert (2003) reported that during the shortening of HRT, contact time between microbial biomass and substrate got reduced and thereby there could be a slight decline in conversion. Due to the change in HRT from 10 to 7 days, initially the reactors showed a decrease in TS and BOD reduction. But within a few days the reactors acquired high TS and BOD reductions. This indicated the ability of the hybrid bioreactors to adapt changes in loading rates.

4.3.3 Start-up of UAHBR after the lock down period

After the operation of UAHBR in 10 and 7 day HRT an interruption for 2 months occurred due to Covid 19 lockdown. When the bioreactors were started up again after 2 months they were operated first at 10 HRT and subsequently reduced to 7 day HRT. During this period the bioreactor operation was monitored by observing the pH of effluent from the reactor. The reactor attained stability within one month period. The pH was stabilised above neutral during this transition periods and this indicated the stability of the bioreactors. This has also proved that the hybrid bioreactor could be restarted easily after a shutdown for few months.

4.3.4 Performance of UAHBR at 5 day HRT

The bioreactors were operated for 2 weeks at 5 day HRT and the performance parameters were observed. The variation of influent and effluent pH along with daily biogas production is shown in Fig 4.5. Even though the influent pH was between 5.6 and 5.8, effluent pH remained above neutral at 5 day HRT in confirmation of achieving a pseudo steady state. Bioreactors gained the maximum effluent pH of 8.1 towards the end of 5 day HRT period and attained daily biogas production and biogas productivity of 108 litres and 4.15 L L^{-1}, respectively (Table 4.7). Biogas productivity decreased with shortening of HRTs whereas daily biogas production increased. Kumbar (2016) obtained a similar biogas productivity of 4.15 L L^{-1} on 6 day HRT for waste coconut water, whereas Bovas (2009) achieved only 1.2 L L^{-1} of biogas productivity at the same HRT for rice mill effluent, which was lower than RLPE and waste coconut water.

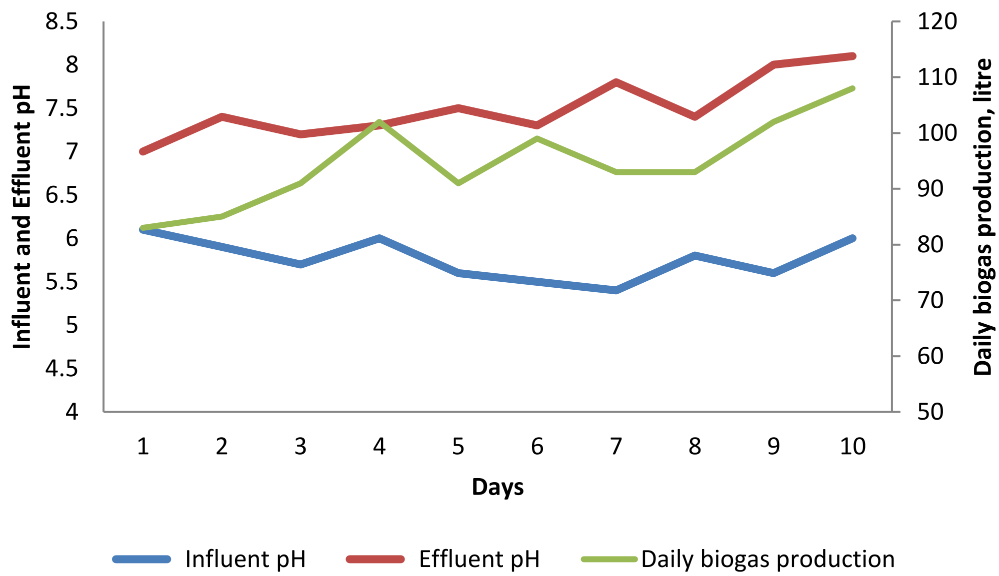

Fig 4.5 Variation of pH and daily biogas production at 5 day HRT period

Table 4.7 Process parameters of UAHBR at 5 day HRT at period

Week	pH (weekly mean)		Daily biogas production *, L	Biogas productivity, L L^{-1}
	Influent	Effluent		
1	5.86	7.28	90.40	3.47
2	5.66	8.10	108.00	4.15

*Weekly mean

Table 4.8 TS and BOD reduction at 5 day HRT period

Week	TS, mg L^{-1}		TS reduction,%	BOD, mg L^{-1}		BOD reduction,%
	Influent	Effluent		Influent	Effluent	
1	9516.38	3901.65	59.00	2836.46	1321.21	53.42
2	10563.59	4100.58	61.18	2250.66	753.65	66.51

Both TS and BOD reduction diminished to 61.18 % and 66.51 % during the 5 day HRT period (Table 4.8). A decrease of 14.12 % and 9.35 % were seen for TS and BOD reductions over the values of 7 day HRT. By comparing these with 10 day HRT period, that reductions were 23.29 % and 11.91 % for TS and BOD reductions, respectively. Effluent from bioreactors had a higher pollutant concentration than for longer HRTs tested previously. James and Kamaraj (2009) obtained TS reduction of 55% and BOD reduction of 98.6% at 6 day HRT for cassava starch factory effluent.

4.3.5 Performance of UAHBR at 3 day HRT

At 3 day HRT the bioreactors exhibited a marked decrease in gas production in the first few days (Fig 4.6). This was due to the sudden change of HLR due to the change in HRT to 3 days. Still the pH of effluent remained above 7.1 during this period and confirmed that reactor was in stable state. At pseudo steady state condition reactors were attained with a daily biogas production of 115 litres (Table 4.9). This showed the steady increase of daily biogas production on shortening of HRTs. Biogas productivity reduced rapidly to 2.61 L L^{-1} in 3 day HRT. This indicated that conversion rate of solids to biogas got reduced on lowering of HRT.

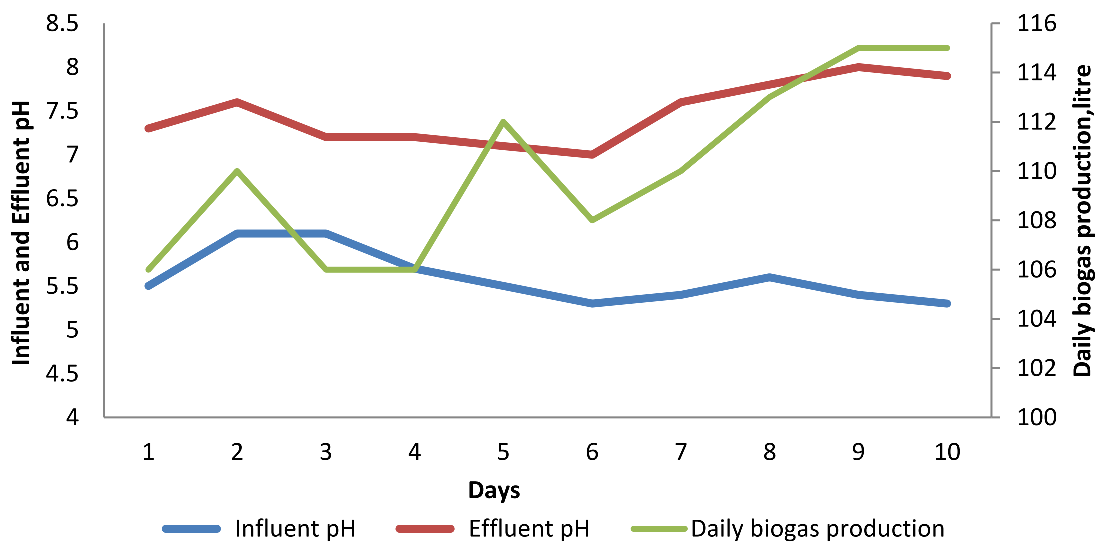

Fig. 4.6 Variation of pH and daily biogas production at 3 day HRT period

Table 4.9 Process parameters of UAHBR at 3 day HRT period

Week	pH (weekly mean)		Daily biogas production *, L	Biogas productivity, L L^{-1}
	Influent	Effluent		
1	5.78	7.28	108.00	2.45
2	5.40	7.66	115.00	2.61

*Weekly mean

Table 4.10 TS and BOD reduction at 3 day HRT period

Week	TS, mg L^{-1}		TS reduction,%	BOD, mg L^{-1}		BOD reduction,%
	Influent	Effluent		Influent	Effluent	
1	10360.96	5723.91	44.75	2600.56	1425.89	45.16
2	11578.75	5660.78	51.88	2040.39	1025.25	49.75

From Table 4.10, it can be seen that BOD reduction was still also going lower at the reduced HRT of 3 day. Bioreactors had BOD and TS reductions of only 49.75% and 51.88%, respectively towards the end of this period.

4.3.6 Performance of UAHBR at 2 day HRT

Change in daily biogas production with influent and effluent pH at 2 day HRT period is shown in Fig. 4.7. At 2 day HRT, pH of effluent could not remain in the alkaline range but reduced to 6.86. Even though the pH was slightly below neutral performance of bioreactors were normal at this HRT also. James and Kamaraj (2009) also obtained effluent pH of 6.9 at 1 day HRT for cassava starch factory effluent but it did not affect the stability of the bioreactor.

It is seen From Table 4.11, that, reactor generated biogas in between 120-125 litres daily, at 2 day HRT. Biogas productivity reduced to the minimum value of 1.96 L L^{-1}. At this HRT, conversion of solid contents in RLPE to biogas reduced to a much lower value.

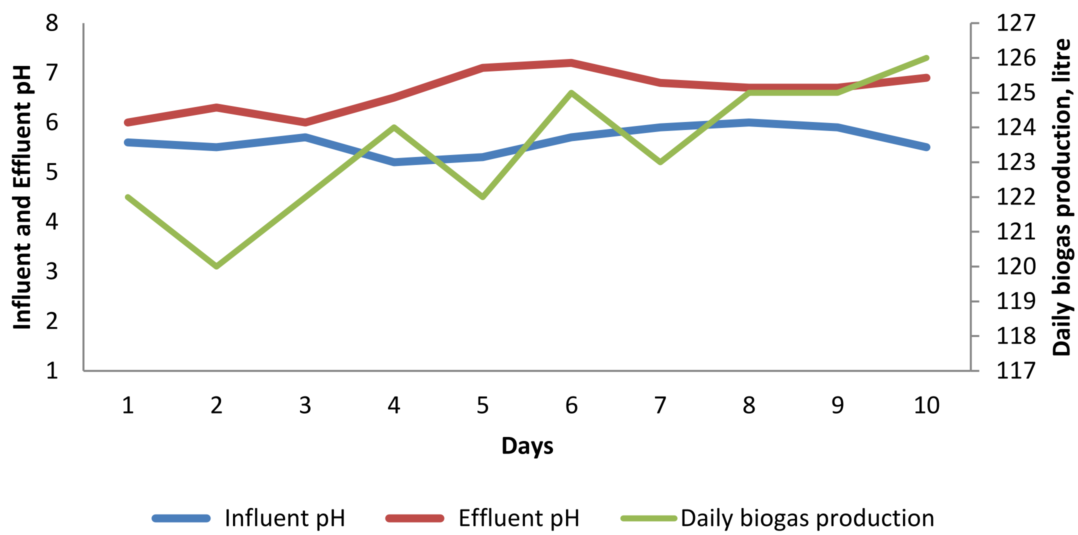

Fig. 4.7 Variation of pH and daily biogas production at 2 day HRT period

Table 4.11 Process parameters of UAHBR at 2 day HRT period

Week	pH (weekly mean)		Daily biogas production *, L	Biogas productivity, L L^{-1}
	Influent	Effluent		
1	5.46	6.38	124.00	1.93
2	5.80	6.86	126.00	1.96

*Weekly mean

Table 4.12 TS and BOD reduction at 2 day HRT period

Week	TS, mg L^{-1}		TS reduction,%	BOD, mg L^{-1}		BOD reduction,%
	Influent	Effluent		Influent	Effluent	
1	11701.75	7227.23	38.23	2627.35	1650.78	37.16
2	11627.81	6701.81	42.36	2536.46	1423.97	43.83

TS and BOD reductions of reactor at 2 day HRT were 42.36 % and 43.83 %, respectively (Table 4.12). Significant decline in TS reduction can be observed at this shortest HRT tested. At transition periods, TS and BOD reduction was low due to change in HRT, but it picked up slightly once the PSS period was reached. James and Kamaraj (2009) reported a higher TS and BOD reductions of 46.1% and 87.5%, respectively at 2.5 day HRT for bioreactors treating cassava starch factory effluent.

4.3.7 Performance of UAHBR at different HRTs

Performance of anaerobic systems treating organic effluents are assessed in terms of effluent pH, TS and BOD reduction, daily biogas production, biogas productivity, volumetric biogas production and specific biogas production.

4.3.7.1 pH variations in different HRTs

The variation of influent and effluent pH at different HRTs is given in Fig. 4.8. RLPE was fed to the bioreactors directly from the collection tank of the rubber latex processing centre. pH of RLPE was not controlled before pumping. But it was seen that the variation in influent pH did not affect the effluent pH. Effluent pH remained above neutral at all HRTs except for the shortest HRT of 2 days, during which it was near neutral. This revealed that reactor was stable up to 2 day HRT. High pH range in effluent showed a good methanogenic activity in reactor and likeliness of having good buffering capacity. The pH has gone above 8 indicating that the bioreactor liquor has attained increased alkalinity. Increased alkalinity improves the buffering action and is advantageous for ensuring stability of the reactor when the feed material is acidic.

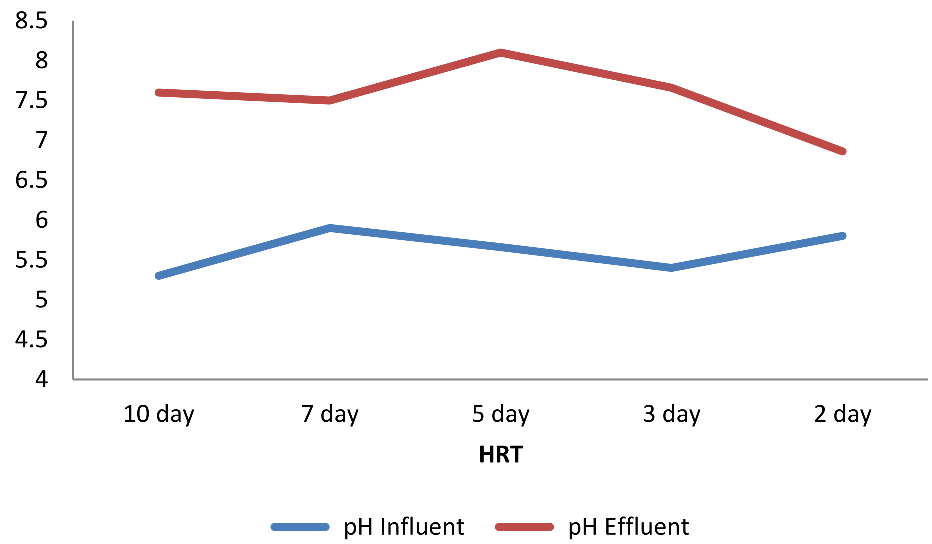

Fig. 4.8 pH of Influent and Effluent at different HRTs

4.3.7.2 TS and BOD reduction at PSS of different HRTs

TS and BOD reduction at different HRTs is depicted in Fig. 4.9. Up to 5 day HRT bioreactors had good reduction in TS and BOD. Beyond the 5 day HRT period, effluent had higher TS and BOD values. From Table 4.13, it is seen that BOD of effluent at 10 day HRT was 600 mg L^{-1} and with shortening of HRT to 2 day, the BOD of effluent increased to 1424 mg L^{-1}. A similar behaviour was observed in the TS of effluent also. Kumbar (2016) also reported similar trend for anaerobic treatment of waste coconut water in UAHBR. Therefore, it can be inferred that beyond 5 day HRT, TS and BOD reductions of UAHBR were not appreciable.

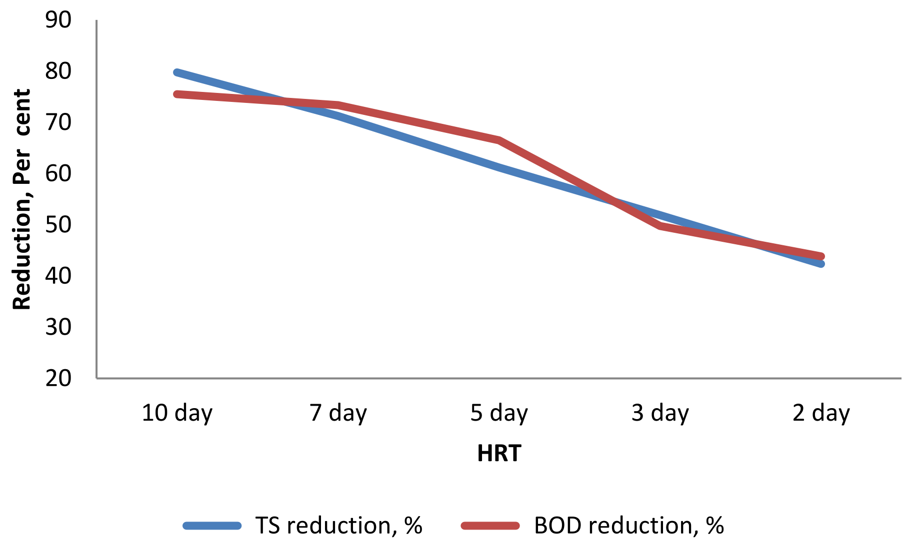

Fig. 4.9 TS and BOD reduction at different HRTs

Table 4.13 TS and BOD reduction at different HRTs

Parameter		HRT				
		10	7	5	3	2
TS, mgL^{-1}	Influent	12340.17	12892.15	10563.59	11578.75	11627.81
	Effluent	2497.50	3512.19	4100.56	5660.78	6701.81
TS reduction, %		79.76	71.24	61.18	51.88	42.36
BOD, $mg\ L^{-1}$	Influent	2700.00	3105.56	2250.66	2040.39	2536.46
	Effluent	600.00	826.84	753.65	1025.25	1423.97
BOD reduction, %		75.50	73.37	66.51	49.75	43.83

4.3.7.3 Biogas production performance of UAHBRs

Gas production parameters of UAHBRs are given in Table 4.14. Daily biogas production and volumetric biogas production were found to increase with reduction in HRT. But biogas productivity per litre of RLPE as well as specific biogas production showed a reducing trend with shortening of HRT.

Table 4.14 Performance of parameters at different HRTs

Parameter	HRT				
	10	7	5	3	2
Daily biogas production, L	63	95	108	115	126
Biogas productivity, L L^{-1}	5.25	5.27	4.15	2.61	1.96
Volumetric biogas production, L m^{-3} d^{-1}	484.61	730.76	830.76	884.61	969.23
Specific biogas production, L kg^{-1} TS_{added}	425.45	403.34	392.85	225.41	166.84

Fig. 4.10 illustrates the effect of shortening of HRT on specific biogas production and volumetric biogas production. Maximum value (425.45 L kg^{-1} TS_{added}) of specific biogas production was obtained at 10 day HRT and minimum value (166.84 L kg^{-1} TS_{added}) was obtained at 2 day HRT. It could be observed that as the loading rate increased the specific biogas production decreased. While specific biogas production decreased with shortening of HRT, the volumetric biogas production showed an increasing trend. The reduction in specific biogas production was due to the lesser TS

reduction indicating that less amount of solids will be gasified at short HRTs. Decrease was rather slow but sharp decrease can be seen at 5 day HRT. As the loading rate progressively increased with reduction in HRT, the total biogas produced from the bioreactor kept on increasing. That is why the volumetric gas production increased with reduction in HRT. Bovas (2009) and James and Kamaraj (2009) reported same trends in reduction of specific biogas production and biogas productivity with decrease in HRT.

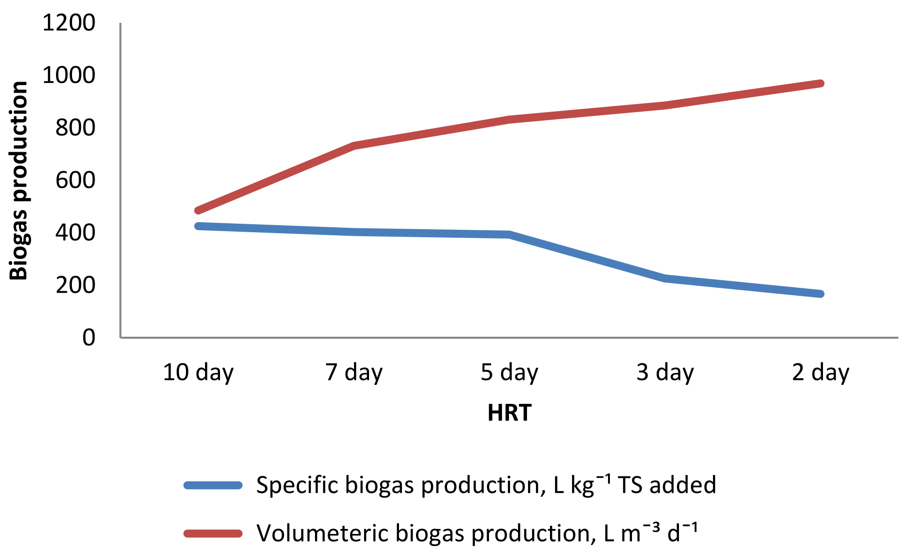

Fig. 4.10 Specific and volumetric gas productions at different HRTs

4.3.7.4 Loading rate at different HRTs

Change in TS and BOD loading rate with respect to hydraulic loading rate are depicted in Fig. 4.11. Up to 5 day HRT, hydraulic loading rate was linear and then increased sharply. TS and BOD loading rates were also increasing with hydraulic loading rate. The significant increase of loading rates affected the reactor performance parameters during the periods beyond 5 day HRT and was most drastic at 2 day HRT.

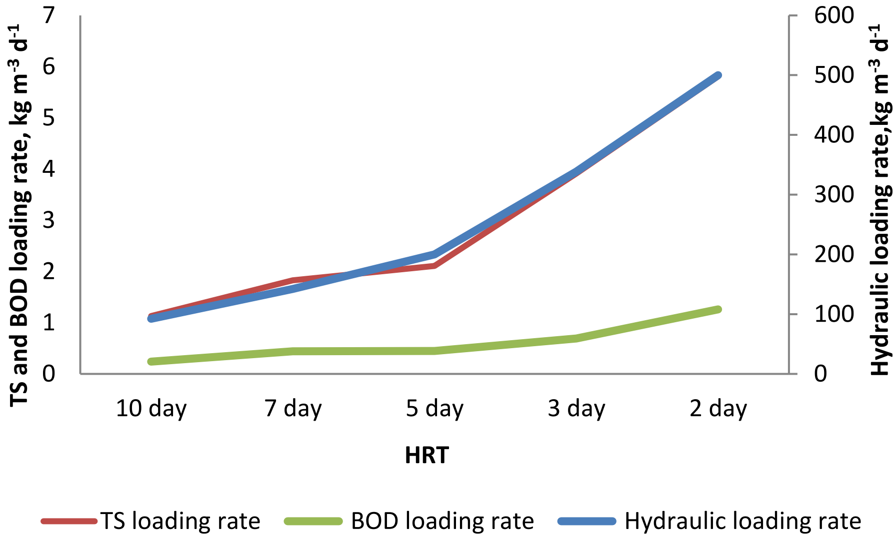

Fig. 4.11 Loading rate at different HRTs

4.3.8 Performance of UAHBRs on progressively increasing the HRT

The bioreactors were operated successively at reduced loading rates corresponding to the longer HRTs after reaching the shortest HRT of 2 day. The reactor performance was assessed by monitoring the biogas production and other performance indicators. Immediately after attaining the pseudo-steady state condition at 2 day HRT, reactor was switched to operate at 3, 5 and 7 day HRTs. Effluent discharged from reactor had above neutral pH as expected and were 7.6, 8.1 and 7.5 at 3, 5 and 7 day HRTs, respectively. Mean daily biogas production at these HRTs, in comparison to the corresponding values obtained when the HRT was progressively reduced, is depicted in Fig. 4.12. It was observed that there was no considerable difference in daily biogas production, indicating that the overall performance did not vary much. This result revealed that the bioreactors would have achieved the maximum possible microbial population already and there was no further improvement in performance on the passage of time. In general the performance of fixed film bioreactors can have a gradually increasing trend as the microbial biomass may continue to multiply. But once the maximum biofilm thickness has achieved, the attached biomass may not further grow.

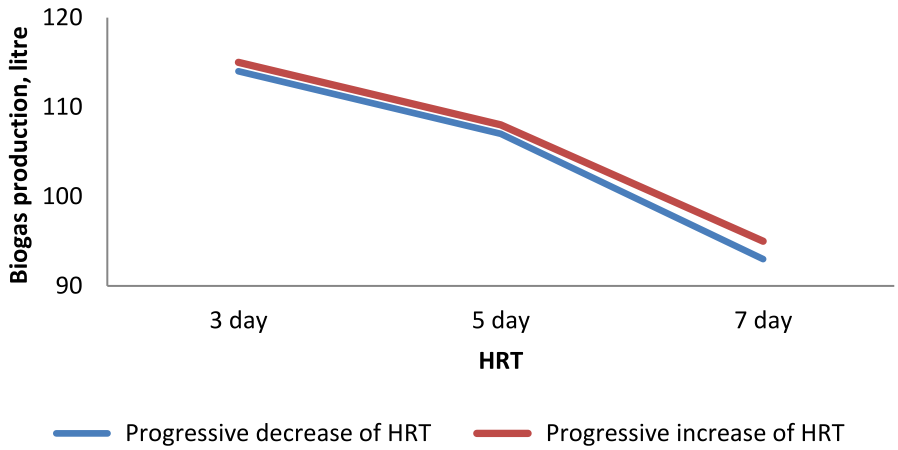

Fig. 4.12 Daily biogas production during progressive increase and decrease of HRTs

4.4 Design criteria for full scale anaerobic bioreactor

The study could demonstrate the successful use of UAHBR technology for energy production from RLPE. Even though the pH of the feed material was acidic no neutralisation was required either for the start up or for the operation of the bioreactors. The above neutral values of the effluent discharged after treatment from the bioreactor further confirmed the suitability of the technology. Due to short HRT of the UAHBR compared to conventional biogas plants, the volume of bioreactor could be significantly reduced resulting in tremendous reduction in cost of construction. Compared to conventional biogas plants the UAHBR was proven to be much advantageous in saving the construction cost as well as producing energy in the form of biogas which can be successfully used for drying rubber sheets produced in the unit.

Results of performance parameters obtained in field scale reactor were useful for forming guidelines to design a full scale anaerobic bioreactor. The UAHBR performance was quite satisfactory at 5 day HRT with respect to pollutant reduction as well as energy production. Start-up of the field scale reactor was with cow dung slurry as inoculum. Cow dung is easily available in the area and can be used as inoculum for start up. The full scale bioreactor also can have broken coconut shells as media for microbial attachment. For the experimental UAHBRs, the upper 37.93% percent of the reactor height was filled with media and a similar design may be adopted for the full scale UAHBR also. The reactor volume may be fixed in consideration of the operational HRT. The materials of construction for reactor can be concrete so as to minimise the cost. Gas holder may be fabricated with FRP and can be integrated with the digester portion of the bioreactor.

Hence the criteria proposed for the construction of a full scale plant for the unit is shown in Fig. 4.13 and Table 4.15.

Dimensions adopted for designing of full scale UAHBR are given below:

Daily feed = 5000 L d^{-1}

Diameter of reactor fixed as 3.5 m

Total liquid volume of reactor excluding media = 25 m^3

Height of reactor without media filling = $25/\Pi r^2$ = 2.6 m

Height of media filled portion considering design media height as 40% =

$2.6 \times 0.4 = 1.04$ m

Additional volume required for media with porosity of 68 % and design media height of 40% = $1.04 \times (1- 0.68) = 0.33$ m

Height of upper media filled portion = 1.04 + 0.33 = 1.4 m

Volume of media filled portion = $\Pi/4\ (3.5^2 x\ 1.4)$ = 13.46 m^3

Quantity of broken coconut shell used with bulk density 410.95 kg m^{-3} =
13.46 x 410.95 = 5531.39 kg

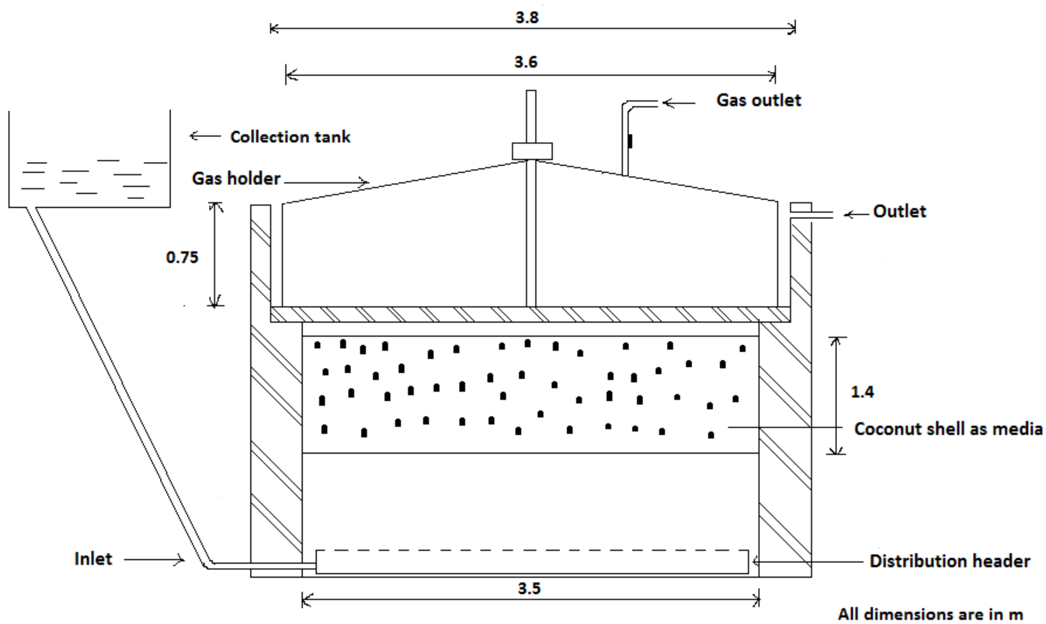

Fig. 4.13 Line diagram of proposed Full scale UAHBR

Table 4.15 Design and operational parameters for full scale UAHBR for RLPE

Operational and design parameters	Particulars	Design values
HRT	5 day	5 day
Reactor volume	110 % of five times Daily effluent quantity	27500 L
Influent pH range	Above 4.5	4.5-6
Effluent pH range	Above 7	7-7.8
Hydraulic loading rate	Daily feed volume per m^3 of reactor	181.81 L m^{-3} d^{-1}
Expected daily gas volume	4.15 times the daily feed	20750 L
Gas holder volume	35% storage volume is provided as the gas produced continuously used for drying sheets	7262 L
Diameter and Height of gas holder	Diameter = 3.6 Height = 0.71 m	3.6m (Dia) X 0.75 m (Height)

The full scale plant can be constructed using the basic design of the field scale bioreactors. But the depth to diameter ratio can be appropriately decided based on the site characteristics and structural parameters. pH of effluent from reactor should be monitored regularly to understand the stability of the bioreactor. Sudden change in loading rates is likely to affect the reactor performance. Therefore, while changing loading rates reactor should be monitored well.

It is adviced to assess the maximum daily waste water generation and design the bioreactor for that volume. Daily on an average 2200 rubber sheets were produced and dried in the factory daily. Average waste water discharge from factory was 5000 litres per day. Total energy from biogas produced from 5000 litre effluent could be estimated as

415 MJ (considering heating value of biogas as 20 MJ per m^3). This energy can be used for drying of rubber sheets. Biogas could be used in a biogas fired drier with an overall thermal efficiency of 60%. Thus biogas from reactor could replace 500 kg of firewood (20% thermal efficiency) per day. This will result in overall reduction in emission from the drying unit of the rubber latex processing plant. Thus, the proposed system is capable of addressing the pollution problem from effluent discharge as well as air pollution from the drying unit of the rubber latex processing plant.

SUMMARY AND CONCLUSION

CHAPTER V

SUMMARY AND CONCLUSION

Kerala is ranked first in India for annual rubber production. Natural rubber is mainly harvested or derived in the form of a milky colloidal suspension or latex. Rubber latex processing plants generally produce large quantity of effluents which contains high amount of degradable organic matter characterised by high BOD, COD and TS. These effluents are often not properly treated in many processing plants before discharged to land. This may affect the local environment resulting in adverse effects on public health. Hence adoption of a suitable and affordable technology for waste stabilization and energy generation is needed. High rate anaerobic bioreactors are capable for anaerobic digestion of high volume agro-processing effluents at reduced hydraulic retention times in the order of few days with maximum biogas production. The present investigation is aimed to study the energy conversion of rubber latex processing effluent (RLPE) and to conduct a detailed investigation in a field scale high rate anaerobic bioreactor so as to form guidelines for the design, installation and maintenance of a full scale anaerobic high rate bioreactor.

Physico-chemical characteristics of RLPE samples were tested and found that RLPE was a very dilute waste water with TS, BOD and COD of 11086.7 mg L^{-1}, 2572.9 mg L^{-1} and 5856 mg L^{-1}, respectively. The pH was in the acidic range and was observed to be in the range of 5.1-6.1. The Volatile Solid content was 2356 mg L^{-1}. BOD: COD ratio of 0.44 obtained in this study showed good biodegradability of RLPE.

A batch anaerobic digestion study was conducted as a preliminary experiment to investigate the biomethanation characteristics of RLPE. The experiment consisted of four treatments having different composition of RLPE replicated thrice. Cow dung slurry was used as inoculum for the 3 treatments whereas effluent collected from a conventional biogas plant was used for the 4^{th} treatment. TS reductions of 56.46 %, 57.47%, 51.08% and 30.63% were obtained from treatment T0, T1, T2 and T3, respectively, in a total batch digestion period of 75 days. The result from T3 showed that the inoculum used in T3 was inferior to ordinary cow dung slurry to be used as inoculum. The final pH of all the treatments reached above neutral values in the range 7.8-8.2. The difference in biomethanation characteristics of treatments was mainly due to the difference in solid contents as well as the difference in proportion of easily biodegradable materials in the substrate. The control treatment (cow dung slurry) had more cumulative biogas production of 14.43 L. Total gas production in T1, T2 and T3 are 9.07 L, 3.80 L and 1.26 L, respectively. Biogas productivity of 3.60, 2.26, 0.95 and 0.315 L L^{-1} was achieved for the treatments T0, T1, T2 and T3, respectively. This study could prove that RLPE could be subjected to biomethanation and cow dung slurry can be used as inoculum. Even at a lower inoculum: substrate ratio of 1:2, the system could be started up yielding substantial amount of biogas coupled with good TS reduction.

Field scale Upflow Anaerobic Hybrid Bioreactors (UAHBR) were installed at a rubber latex processing factory at Anamangad, Malappuram and performance was assessed by operating them at varying HRTs. The UAHBRs had a hybrid design incorporating the concepts of Anaerobic Filter and UASB reactor. The upper 37.93% of the reactor height was filled with broken coconut shells as media for microbial cell immobilisation. Semi continuous feeding of RLPE was commenced with 12 litre per day corresponding to 10 day HRT. The bioreactors were operated at 10, 7, 5, 3 and 2 day HRT. During the study an interruption of 2 months in operation occurred due to shut down of the processing unit due to Covid 19.

Effluent pH remained above neutral at all HRTs. Variation in influent pH did not affect the effluent pH indicating that the bioreactors were stable even at 2 day HRT. The elevation of effluent pH to alkaline range showed a good methanogenic activity in the bioreactors and likeliness of having good buffering capacity.

Reactor achieved maximum TS and BOD reduction of 79.76% and 75.5%, during 10 HRT. Up to 5 day HRT bioreactors had good reduction in TS and BOD. After the 5 day HRT period, effluent had high TS and BOD value. Therefore, it could be inferred that beyond 5 day HRT, TS and BOD reduction of UAHBR was not appreciable.

Biogas productivity at 10, 7, 5, 3 and 2 HRTs were 5.25, 5.27, 4.15, 2.61 and 1.96 L L^{-1} respectively. An increase of daily biogas production and volumetric biogas production with reduction in HRT was observed. Reactor achieved maximum volumetric biogas production of 484.61 L m^{-3} d^{-1} at 10 day HRT. But biogas productivity per litre of RLPE as well as specific biogas production showed a reduction with shortening of HRT. The reduction in specific biogas production was due to the lesser TS reduction indicating that less amount of solids will be gasified at short HRTs.

Up to 5 day HRT, hydraulic loading rate was linear and then increased sharply. TS and BOD loading rates also increased with hydraulic loading rate. The significant increase of loading rates affected the reactor performance parameters beyond 5 day HRT period.

The bioreactors were operated successively at reduced loading rates corresponding to the longer HRTs after reaching the shortest HRT of 2 day. Even though there was a small improvement observed, there was no considerable difference in daily biogas production with the earlier values obtained during the progressive decrease in HRT. This indicated that the overall performance did not vary considerably during both modes of HRT changes. This also revealed that the bioreactors would have achieved the maximum possible microbial population already and there was only small improvement in performance within the passage of time.

The easy start up and satisfactory performance of the bioreactor to reach a short HRT of 5 days, after a shut down for two months due to Covid 19 also could prove the superiority of the hybrid design.

Results of performance parameters obtained in field scale reactors were used for forming guidelines in designing a full scale anaerobic bioreactor. The UAHBR performance was quite satisfactory at 5 day HRT with respect to pollutant reduction as well as energy production. Hence as criteria, full scale plant was proposed to be operated at 5 day HRT with 27 m^3 reactor volume and 7.2 m^3 of gas holder volume.

Daily an average of 2200 rubber sheets was produced and dried in the factory. Average waste water discharge from factory was 5000 litres. Total energy from biogas produced from 5000 litre effluent could be estimated as 415 MJ which was proposed to be used for drying rubber sheets. Biogas can be used in a biogas fired drier with an overall thermal efficiency of 60%. Thus biogas which can be produced from the envisaged full scale bioreactor could replace 500 kg of firewood (20% thermal efficiency) per day.

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APPENDICES

APPENDIX I

Daily gas production (mL) for batch digestion study

Days	T0			T1		
	A	B	C	A	B	C
1	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	15.4	0.0	30.8	0.0	0.0
3	0.0	0.0	0.0	0.0	30.8	15.4
4	30.8	15.4	61.5	46.1	76.9	76.9
5	30.8	15.4	46.2	15.4	61.5	61.5
6	46.2	76.9	46.2	15.4	92.3	61.5
7	15.4	0.0	30.8	123.0	153.9	123.1
8	15.4	15.4	30.8	169.2	230.8	169.2
9	15.4	15.4	15.4	307.7	461.6	307.7
10	0.0	15.4	46.2	215.4	615.4	215.4
11	15.4	0.0	30.8	353.8	338.5	461.6
12	15.4	15.4	15.4	461.5	292.3	538.5
13	15.4	15.4	61.5	553.9	246.2	569.3
14	0.0	0.0	0.0	646.2	123.1	307.7
15	15.4	15.4	15.4	692.3	76.9	261.6
16	46.2	46.2	107.7	661.5	230.8	323.1
17	61.5	61.5	0.0	569.2	123.1	153.9
18	46.2	61.5	46.2	507.7	200.0	153.9
19	76.9	92.3	61.5	461.5	153.9	184.6
20	92.3	92.3	123.1	384.6	200.0	153.9
21	153.9	169.2	153.9	353.8	138.5	61.5
22	138.5	107.7	123.1	246.1	15.4	92.3
23	153.9	153.9	153.9	153.8	169.2	153.9
24	246.2	215.4	261.6	123.0	169.2	153.9
25	307.7	246.2	230.8	76.93	123.1	107.7
26	353.9	307.7	246.2	76.93	92.3	61.5
27	415.4	338.5	353.9	138.4	92.3	92.3
28	461.6	415.4	415.4	107.7	107.7	92.3
29	538.5	461.6	507.7	46.1	107.7	107.7
30	769.3	461.6	692.4	76.9	169.2	107.7
31	830.8	692.4	753.6	30.8	107.7	30.8
32	923.2	830.8	753.6	76.9	92.3	76.9
33	923.2	753.6	692.4	76.9	92.3	46.2
34	907.8	830.8	923.2	15.4	15.4	15.4
35	815.5	815.5	830.8	76.9	46.2	46.2
36	753.9	615.4	538.5	76.9	30.8	30.8
37	615.4	538.5	430.8	61.5	76.9	92.3

38	600.1	200.0	230.8	30.8	0.0	30.8
39	538.5	153.9	246.2	61.5	61.5	46.2
40	492.4	123.1	261.1	61.5	15.4	30.8
41	430.8	107.7	246.2	76.9	0.0	30.8
42	338.5	169.2	169.2	76.9	15.4	15.4
43	307.7	92.3	107.7	30.8	46.2	46.2
44	246.2	107.7	123.1	30.8	15.4	0.0
45	261.1	169.2	169.2	76.9	0.0	61.5
46	169.2	123.1	138.5	61.5	15.4	0.0
47	107.7	107.7	46.2	30.8	0.0	0.0
48	123.1	61.5	92.3	30.8	0.0	46.2
49	107.7	30.8	30.8	30.8	0.0	30.8
50	92.3	46.2	61.5	30.8	0.0	0.0
51	76.9	0.0	15.4	61.5	0.0	0.0
52	92.3	0.0	0.0	15.4	0.0	0.0
53	61.5	0.0	15.4	15.4	0.0	0.0
54	15.4	1.4	0.0	30.8	0.0	0.0
55	61.5	15.4	15.4	0.0	30.8	15.4
56	92.3	15.4	46.2	15.4	15.4	15.4
57	15.4	15.4	15.4	0.0	15.4	15.4
58	46.2	15.4	15.4	15.4	0.0	15.4
59	15.4	15.4	15.4	15.4	15.4	15.4
60	30.8	15.4	30.8	0.0	0.0	15.4
61	0.0	15.4	15.4	15.4	0.0	0.0
62	0.0	0.0	0.0	15.4	0.0	0.0
63	15.4	15.4	15.4	15.4	15.4	15.4
64	30.8	30.8	15.4	15.4	15.4	15.4
65	15.4	30.8	15.4	0.0	15.4	0.0
66	15.4	15.4	15.4	15.4	0.0	15.4
67	30.8	15.4	15.4	15.4	15.4	30.8
68	15.4	15.4	46.2	30.8	0.0	15.4
69	15.4	30.8	15.4	15.4	15.4	0.0
70	15.4	15.4	30.8	15.4	15.4	15.4
71	30.8	30.8	15.4	0.0	15.4	15.4
72	15.4	15.4	15.4	30.8	0.0	30.8
73	30.8	15.4	15.4	30.8	15.4	15.4
74	15.4	30.8	15.4	30.8	0.0	0.0
75	15.4	15.4	15.4	0.0	0.0	0.0

Days	T2			T3		
	A	B	C	A	B	C
1	0.0	0.0	0.0	0.0	0.0	0.0
2	30.8	30.8	30.8	0.0	0.0	0.0
3	46.1	46.2	30.8	0.0	0.0	0.0
4	0.0	0.0	61.5	0.0	0.0	46.2
5	61.5	61.5	30.8	76.9	76.9	15.4
6	61.5	61.5	61.5	138.4	46.2	30.8
7	138.4	138.5	153.9	169.2	46.2	15.4
8	76.9	76.9	92.3	76.9	76.9	30.8
9	169.2	169.2	184.6	46.1	46.2	76.9
10	107.7	107.7	107.7	0.0	138.4	123.1
11	153.8	153.9	123.1	15.4	46.2	138.5
12	61.5	61.5	61.5	15.4	30.8	92.3
13	123.0	123.1	46.2	0.0	30.8	76.9
14	76.9	76.9	107.7	30.8	0.0	46.2
15	123.0	123.1	107.7	15.4	15.4	30.8
16	230.7	230.8	169.2	0.0	0.0	30.8
17	276.9	276.9	184.6	46.2	0.0	15.4
18	323.1	184.6	215.4	30.8	0.0	15.4
19	461.5	276.9	384.6	15.4	0.0	30.8
20	276.9	323.1	353.8	30.8	0.0	15.4
21	123.0	261.6	246.2	30.8	0.0	46.2
22	76.9	169.2	169.2	0.0	0.0	15.4
23	61.5	123.1	123.1	0.0	0.0	15.4
24	46.1	46.2	76.9	0.0	0.0	46.2
25	30.8	76.9	61.5	0.0	0.0	15.4
26	61.5	15.4	30.8	15.3	15.4	15.4
27	30.8	30.8	61.5	0.0	0.0	15.4
28	0.0	0.0	15.4	0.0	0.0	30.8
29	30.8	30.8	61.5	46.1	46.2	30.8
30	30.8	30.8	15.4	30.8	30.8	15.4
31	76.9	76.9	0.0	15.3	15.4	30.8
32	0.0	76.9	0.0	61.5	61.5	30.8
33	15.4	15.4	46.2	0.0	0.0	30.8
34	0.0	0.0	0.0	0.0	0.0	15.4
35	15.4	15.4	30.8	0.0	0.0	15.4
36	0.0	0.0	0.0	30.8	30.8	15.4
37	30.8	30.8	0.0	15.3	15.4	30.8
38	0.0	0.0	15.4	30.8	30.8	15.4
39	30.8	30.8	46.2	0.0	0.0	15.4
40	0.0	0.0	0.0	15.3	15.4	15.4

41	0.0	0.0	0.0	15.4	15.4	15.4
42	0.0	0.0	0.0	15.4	15.4	15.4
43	15.4	15.4	30.8	15.4	15.4	0.0
44	0.0	0.0	0.0	15.4	15.4	15.4
45	15.4	15.4	15.4	0.0	0.0	0.0
46	0.0	0.0	15.4	46.1	46.2	46.2
47	15.4	15.4	0.0	15.4	15.4	30.8
48	0.0	0.0	15.4	15.4	15.4	0.0
49	0.0	0.0	15.4	30.8	30.8	15.4
50	0.0	0.0	46.2	0.0	0.0	15.4
51	15.4	15.4	15.4	15.4	15.4	0.0
52	0.0	0.0	0.0	15.4	15.4	30.8
53	0.0	0.0	0.0	15.4	15.4	0.0
54	0.0	0.0	15.4	0.0	0.0	15.4
55	15.4	15.4	0.0	0.0	0.0	0.0
56	15.4	15.4	0.0	0.0	0.0	30.8
57	15.4	15.4	15.4	15.4	15.4	0.0
58	0.0	0.0	15.4	15.4	15.4	15.4
59	15.4	15.4	15.4	15.4	15.4	0.0
60	0.0	0.0	15.4	15.4	15.4	30.8
61	0.0	0.0	30.8	0.0	0.0	0.0
62	30.8	30.8	15.4	30.8	30.8	0.0
63	30.8	30.8	30.8	15.4	15.4	30.8
64	15.4	15.4	15.4	0.0	0.0	0.0
65	15.4	15.4	0.0	0.0	0.0	15.4
66	15.4	15.4	0.0	30.8	30.8	15.4
67	0.0	0.0	0.0	30.8	30.8	15.4
68	30.8	30.8	30.8	15.4	15.4	30.8
69	15.4	15.4	30.8	15.4	15.4	0.0
70	15.4	15.4	15.4	15.4	15.4	0.0
71	15.4	15.4	15.4	0.0	0.0	15.4
72	0.0	0.0	15.4	30.8	30.8	15.4
73	30.8	30.8	0.0	0.0	30.8	30.8
74	0.0	15.4	0.0	0.0	15.4	15.4
75	0.0	15.4	0.0	0.0	15.4	0.0

APPENDIX II

Biogas production and Biogas productivity of UAHBR at different HRT

HRT	Days	Biogas production, L	Biogas productivity, L L^{-1}
10 day	1	16	1.33
	2	31	2.58
	3	26	2.17
	4	35	2.92
	5	32	2.67
	6	17	1.42
	7	28	2.33
	8	26	2.17
	9	21	1.75
	10	24	2.00
	11	30	2.50
	12	13	1.08
	13	21	1.75
	14	33	2.75
	15	36	3.00
	16	30	2.50
	17	31	2.58
	18	30	2.50
	19	16	1.33
	20	36	3.00
	21	36	3.00
	22	42	3.50
	23	45	3.75
	24	51	4.25
	25	52	4.33
	26	52	4.33
	27	48	4.00
	28	54	4.50
	29	63	5.25
	30	55	4.58
	31	51	4.25
	32	54	4.50
	33	51	4.25
	34	55	4.58
	35	60	5.00
	36	59	4.91

	37	59	4.91
	38	61	5.08
	39	63	5.25
	40	63	5.25
7 day	1	60	3.33
	2	66	3.66
	3	51	2.83
	4	74	4.11
	5	60	3.33
	6	66	3.66
	7	60	3.33
	8	69	3.83
	9	76	4.22
	10	73	4.05
	11	69	3.83
	12	69	3.83
	13	69	3.83
	14	80	4.44
	15	81	4.5
	16	82	4.55
	17	83	4.61
	18	95	5.27
5 day	1	83	3.19
	2	85	3.26
	3	91	3.50
	4	102	3.92
	5	91	3.50
	6	99	3.80
	7	93	3.57
	8	93	3.57
	9	102	3.92
	10	108	4.15

3 day	1	106	2.40
	2	110	2.50
	3	106	2.40
	4	106	2.40
	5	112	2.54
	6	108	2.45
	7	110	2.50
	8	113	2.56
	9	115	2.61
	10	115	2.61
2 day	1	122	1.90
	2	120	1.87
	3	122	1.90
	4	124	1.93
	5	122	1.90
	6	125	1.95
	7	123	1.92
	8	125	1.95
	9	125	1.95
	10	126	1.96

APPENDIX III

Gas production on progressive increase of HRT

HRT	Days	Biogas production, L	Biogas productivity, $L\ L^{-1}$
3 day	1	106	2.40
	2	112	2.54
	3	108	2.45
	4	110	2.50
	5	113	2.56
	6	114	2.59
	7	114	2.59
5 day	1	85	3.26
	2	91	3.50
	3	102	3.92
	4	91	3.50
	5	99	3.80
	6	93	3.57
	7	102	3.92
	8	107	4.11
7 day	1	76	4.22
	2	73	4.05
	3	69	3.83
	4	69	3.83
	5	69	3.83
	6	80	4.44
	7	81	4.5
	8	82	4.55
	9	91	5.05
	10	93	5.16

ABSTRACT

INVESTIGATIONS ON HIGH RATE ANAEROBIC BIOREACTOR FOR ENERGY PRODUCTION FROM RUBBER LATEX PROCESSING EFFLUENT

by

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ABSTRACT OF THE THESIS

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ABSTRACT

Agro-processing industries often contribute significantly in pollution due to discharge of untreated effluents. By anaerobic digestion of these organic effluents, methane rich gas can be produced which is suitable to generate electricity and process heat. But conventional biogas plants are slow in operation with long hydraulic retention times of 35 to 40 days which necessitates large digester volumes. So, anaerobic digestion of high volume agro-processing effluents is feasible only through high rate bioreactors which can reduce hydraulic retention time to few hours. Rubber latex processing effluent (RLPE) is a dilute waste water for which high rate anaerobic treatment can be an affordable technology. Hence, an investigation was taken up to study the performance of Up-flow Anaerobic Hybrid Bioreactor for energy conversion of rubber latex processing effluent (RLPE).

Physico-chemical characteristics of RLPE samples were tested and found that RLPE was a dilute waste water with pH in the acidic range. BOD: COD ratio of 0.44 obtained in this study showed good biodegradability of RLPE. A batch anaerobic digestion study was conducted as a preliminary experiment to investigate the biomethanation characteristics of RLPE. The experiment consisted of four treatments having different composition of RLPE with inoculums replicated thrice. This study could prove that RLPE could be subjected to biomethanation and cow dung slurry can be used as inoculum. Even at a lower inoculum: substrate ratio of 1:2, the system could be started up yielding substantial amount of biogas coupled with good TS reduction.

Performance of field scale Up-flow Anaerobic Hybrid Bioreactors (UAHBR) was assessed by operating them at different HRTs of 10, 7, 5, 3 and 2 day. During the study an interruption of 2 months in operation occurred due to shut down of the processing unit due to Covid 19. After interruption of 2 months reactor recovered within one month and it proved that hybrid bioreactor could be restarted easily after a shutdown for few months. Reactor was stable in operation during 10, 7, 5, 3 and 2 day HRTs and exhibited good process efficiency with better pollutant reduction and biogas production.

Performance was seen deteriorated beyond 5 day HRT.

The bioreactors were operated successively at reduced loading rates corresponding to the longer HRTs after reaching the shortest HRT of 2 day. It was observed that there was no considerable difference in daily biogas production with the earlier values obtained during the progressive decrease in HRT. This revealed that the bioreactors would have achieved the maximum possible microbial population already and there was no further improvement in performance on further passage of time.

The performance parameters obtained in the investigations with field scale reactors were used for evolving guidelines to design a full scale anaerobic bioreactor. The UAHBR performance was quite satisfactory at 5 day HRT with respect to pollutant reduction as well as energy production. Hence as criteria, full scale plant was proposed to be operated at 5 day and the corresponding reactor volume was 27 m^3 with 7.2 m^3 gas holder volume. The biogas expected to be produced from the full scale plant can be used in a biogas fired rubber sheet dryer which can save about 500 kg of fire wood per day currently used for drying rubber sheets.