Performance assessment of combination of an upflow anaerobic sludge blanket reactor and high rate algal pond for complete sewage treatment

Pritha Chatterjee[1], Sumat C. Jain[1], Chattulaal Maity[1], M.M. Ghangrekar[1,], A. Real[2], C. A. Aragon[2], I. Martin[2] and J.J. Salas[2]*

[1]- Department of Civil Engineering, Indian Institute of Technology, Kharagpur – 721302. India.
[2]- Centre for New Water Technologies (CENTA). Autovia Sevilla-Huelva, km.28. 41820. Carrión de los Céspedes (Sevilla). Spain.
*-Corresponding author: Tel.: +91-3222-283440; Fax: 03222-282254, E-mail: ghangrekar@civil.iitkgp.ernet.in

Abstract
This study aimed at assessing the performance of a pilot-scale upflow anaerobic sludge blanket (UASB) reactor followed by a high rate algal pond (HRAP) to remove organic matter, nutrients and pathogen from sewage and facilitate reuse. Sampling was carried out at different heights of the UASB reactor (inlet, 0.2 m, 1.2 m, 2.2 m, 3.2 m, 4.2 m and outlet), and profile concentrations were determined for organic matter and solids. First-order kinetics showed the best fit to the decay of concentrations of chemical oxygen demand (COD) in the UASB reactor, after it reached steady state. For an influent COD concentration of 233 ± 20 mg L^{-1}, the effluent COD concentration was 75 ± 15. Successful biomass granulation was observed in the sludge bed of the UASB reactor. After reaching steady performance in HRAP, ammonia removal increased to 85.1 ± 2.4% with influent ammonia nitrogen concentrations of 20 ± 3 mg/L and effluent ammonia nitrogen concentration of 3 ± 1 mg/L. Phosphate removal after treatment in the HRAP was 91 ± 1%. There was a 4 log scale pathogen removal after treatment with HRAP with MPN of the final effluent being less than 1000/100 ml, which is within acceptable standards for surface irrigation. The blackwater after treatment using UASB/HRAP is being reused for gardening and landscaping.

Keywords: Anaerobic treatment; disinfection; kinetics; reuse; UASB/pond system; organic matter removal

INTRODUCTION

Population growth, industrialization, agricultural practices and urbanization all increase the water demand and thus the quantity of wastewater generated. Water scarcity is becoming an acute problem in several countries. Traditionally, wastewater treatment has focused on pollution abatement, public health protection and environmental protection by removing biodegradable material, nutrients and pathogens (Meneses et al., 2010). Wastewater recycling, reuse and resource recovery can be a very good approach to conserve water particularly in areas of water shortage (Azizi et al., 2013; Moawad et al., 2009). Various options for treatment and reuse of water like water resources (reclaimed water); energy (methane from anaerobic digestion) and materials (biosolids and nutrients) are currently being researched, developed and implemented worldwide. Developing countries like India and China are gaining momentum in using treated water for potable and non-potable supplies and decentralised treatment units are very helpful in these cases (Mankad & Tapsuwan, 2011). The reclaimed water application governs the type of treatment needed to protect public health and environment and the degree of reliability required to treatment processes and operation (Moawad et al., 2009).

Conventional sewage treatment processes involve high capital, maintenance and operational cost, huge energy requirements, which makes them unsuitable for use in developing countries (Sato et al., 2006). Energy efficient low-cost waste treatment systems are the best choice for such countries. Anaerobic treatment systems excel in such respect. UASB reactors are the most widely used high rate anaerobic sewage treatment process and several full scale reactors have been operated world-wide (Buntner et al., 2013; Lim & Kim, 2014). Most of the successful applications of UASB reactors are to treat high strength industrial wastewaters (Lim & Kim, 2014). Municipal sewage treatment using UASB reactors is restricted to tropical regions where temperature of the raw sewage allows fast hydrolysis of organic matters and suspended solids (Zhang et al., 2013). Sato et al. (2006) evaluated the treatment efficiency of the sixteen UASB reactor based sewage treatment plants on the Yamuna river basin in India and observed that none of the plants met the discharge standards for biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS) or nutrients as total Kjeldahl nitrogen (TKN). The discharge standards for BOD, COD, SS and TKN are 30 mg/L, 250 mg/L, 100 mg/L and 100 mg/L, respectively (CPCB, 1993). In order to improve the effluent quality up to disposal standards, polishing ponds with short retention time were used to treat the UASB effluent. Unfortunately, effluent quality did not follow the desired standard limits even after the polishing ponds (Sato et al., 2006).

In the present study, the possibility of producing reusable quality treated wastewater by a combined UASB-HRAP system is explored. While UASB will help in organic matter removal, HRAP will abate nutrients and pathogens. Microalgal cultivation generally requires inorganic nutrients and carbon dioxide in the presence of sunlight through photosynthesis. These organisms can also be used to accumulate nutrients, as they require less than one-tenth of the area to recover P compared to terrestrial crops (Mehta et al., 2015). As microalgae require both organic and inorganic nutritional inputs for their survival, wastewater can be a potential source of these nutritional requirements and hence forth micro-algae can help in bioremediation of UASB treated wastewater (Kiran et al., 2014). Microalgae also have broad bioenergy potential as they can be used to produce liquid transportation and heating fuels, such as biodiesel and ethanol, or anaerobically digested to produce biogas. The treated wastewater after UASB-HRAP can be used for landscape irrigation (parks, playgrounds, and school yards), fire protection, construction, ornamental fountains, recreational impoundments; in-building uses (toilets, air conditioning).

MATERIALS AND METHODS

Pilot plant description and operation

A novel combination of UASB reactor and HRAP was designed and constructed for treatment of sewage and performance was evaluated to examine the removal of organic matter and nitrogen transformation processes (Figure 1). The UASB reactor was having a height of 5.3 m and diameter of 5.6 m, which is followed by a 15.8 m long and 7.9 m wide HRAP. The UASB/HRAP system was fed with domestic sewage generated in IIT Kharagpur campus, India. The sewage was passed through a screen located upstream the UASB reactor. The pilot UASB reactor was inoculated with septic tank sludge. It was operated at gradually increasing organic loading rates in the start-up phase. The HRAP was operated at a constant HRT of 8 days.

Figure 1: (a) UASB reactor, (b) HRAP

Monitoring

During monitoring, analyses of raw sewage, samples from five sampling ports inside the UASB reactor, effluent from the UASB reactor and final effluent from the secondary settling tank after the algal pond were performed. The analysed parameters were: chemical oxygen demand (COD, total and soluble), total suspended solids (TSS), volatile suspended solids (VSS), alkalinity, volatile fatty acids (VFA), pH, total kjeldahl nitrogen (TKN), nitrate nitrogen and temperature. The analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Total dissolved solids (TDS), pH and NO_3^--N were measured using electrodes (Thermo, USA). Turbidity was measured by Systronics Turbidity Meter. Biogas production was measured continuously by water displacement method.

The characterization of biomass was done for the UASB reactor, with the determination of extracellular polymers, sludge volume index (SVI), sludge settling velocity and specific methanogenic activity (SMA) of the sludge. Settling velocity and strength of the sludge was measured following the procedure described by Ghangrekar et al. (1996) and Bhunia and Ghangrekar (2008a). The results were expressed in terms of an integrity coefficient defined as, the ratio of solids in the supernatant to the total weight of the granular sludge, expressed in percentage. Settling velocity of sludge settled at bottom of settling column at fixed time intervals (0.5, 1, 2, 3, 5, 7, 15, 30, and 60 min) was considered to determine corresponding size (d_P) of biomass fractions, using Newton's law of particle settling theory as mentioned by Bhunia and Ghangrekar (2007). From percentage mass fractions of settled sludge at different time intervals, mean diameter of particles present in the sludge was calculated. Sludge produced, sludge yield and solid retention time (SRT) in the UASB reactor was calculated as described by Chatterjee et al. (2016). For algal biomass harvested protein, lipid, carbohydrate, chlorophyll a, chlorophyll b and algal biomass were determined. Protein (PN) content in algal biomass was measured by Bradford assay (Bradford, 1976) and polysachharide (PS) by Anthrone method (Morris, 1948).

RESULTS AND DISCUSSION

General performance

The UASB reactor was operated for a total of 250 days. After an initial start-up period with gradually improving performance the system stabilised and remained in pseudo steady state until the end of the experimental period. COD profile was evaluated over reactor height. Majority of COD reduction took place only within 2 m from the bottom of the reactor (Figure 2a), which is also corroborated by the pH profile (Figure 2b). COD removal efficiency kept on increasing with operation time, with a maximum soluble COD removal of 73 ± 6% and maximum total COD removal of 66 ± 10%, in the month of June. Average effluent COD throughout the entire range of operation was 75 ± 15 mg/L.

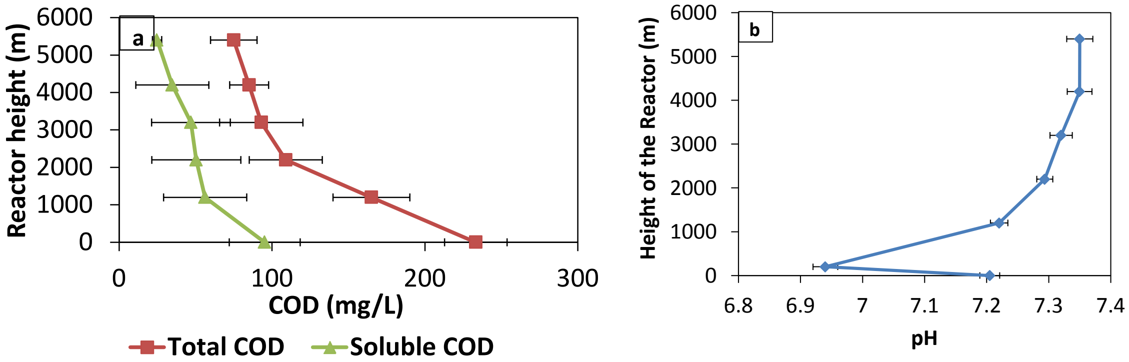

Figure 2: Typical (a) COD and (b) pH profile along the height of UASB reactor

It was observed that the pH at the bottom of the reactor was lower than the pH at the top portion of the reactor. Low pH at the sludge bed zone is due to slight acidification of substrate at this zone. As the wastewater moved upward, the VFA produced was utilized by the methanogens and resulted in increase of pH due the generated alkalinity from the reaction. The variation in slope of pH profile indicates presence of biochemical reactions within the reactor. Hence, it is evident from Figure 2 that major biochemical reactions occur within the bottom 2 m of the reactor that is the sludge bed and sludge blanket zone.

Biogas production rate was measured by water displacement method and methane content was measured by passing biogas through 5% NaOH solution. The average gas production rate was 0.39 ± 0.10 m^3/kg COD removed. The produced biogas is mainly responsible for mixing inside the reactor, which is essential for proper distribution of substrate and to avoid any short circuit. Theoretical biogas production should have been 0.62 m^3/kg COD removed. Due to low gas production rate and intermittent measurement of biogas some error might have caused lower biogas measurement. Methane content in the biogas was 68%.

VSS concentration in the sludge bed of the UASB reactor, after reaching steady state was 30 ± 7 g/L. A higher solid retention time (SRT) is required in anaerobic treatment processes like UASB reactor as compared to the aerobic ones. The potential of UASB reactor is mainly governed by the amount of sludge that can be retained within the reactor. In turn SRT is strongly dependent on the settling characteristics of the sludge. The average SRT during the entire range of operation was around 150 days and average sludge yield was less than 0.3 kg VSS/kg COD removed. Average TSS and VSS in the effluent of the UASB reactor was 31 ± 17 mg/L and 20 ± 10 mg/L, respectively.

Table 1 shows the monthly mean concentrations of total and soluble COD, in the influent and effluent of the UASB reactor. The average values for influent COD were 167 mg/L, 177 mg/L, 218 mg/L and 214 mg/L, respectively in the late autumn months, winter months, spring months and summer months, where the respective mean temperatures were 25, 13, 25 and 33 ºC. Higher temperatures contributed to improve the performance of the reactor and to obtain lower effluent COD concentration. The maximum rate of bacterial growth decreases 11% per 1 ºC for anaerobic digesters operated below 30 ºC (Pontes et al., 2014).

Table 1: Monthly average of COD removal in the UASB reactor

Month	COD inlet (mg/L)	COD outlet (mg/L)	Total COD removal (%)	Soluble COD inlet (mg/L)	Soluble COD outlet (mg/L)	Soluble COD removal (%)	Remarks
Nov	167 ± 30	123 ± 30	27 ± 12	110 ± 12	77 ± 12	30 ± 8	Reactor getting commissioned
Dec	162 ± 30	79 ± 41	49 ± 26	94 ± 21	35 ± 7	63 ± 7	Performance improved
Jan	193 ± 26	98 ± 19	49 ± 9	95 ± 3	39 ± 1	59 ± 1	Sludge washout due to reduced temperature and performance instability
Feb	187 ± 61	76 ± 17	56 ± 16	78 ± 23	33 ± 13	57 ± 9	Performance getting stabilized
Mar	250 ± 61	100 ± 18	58 ± 12	101 ± 21	38 ± 7	63 ± 10	Improving Performance
April	195 ± 49	71 ± 11	61 ± 11	83 ± 19	23 ± 2	70 ± 8	Improving Performance
May	215 ± 44	78 ± 31	63 ± 14	91 ± 29	23 ± 3	72 ± 7	Improving Performance
June	233 ± 20	75 ± 15	66 ± 10	95 ± 23	25 ± 3	73 ± 6	Improving Performance

Decrease of stability constant (ρ) that is the ratio of VFA and alkalinity in anaerobic digestion processes indicates process stability (Nikolaeva et al., 2009; Owamah & Izinyon, 2015). When the VFA/alkalinity ratio exceeds 0.4, due to organic overloading (i.e. the rate of methane generation could not catch up with the rate of acid production) and could cause failure in digestion. This stability constant was higher than 0.4 in the start-up phase of November, December and January, indicating reduced activity of methanogens, leading to a higher COD in the effluent, even at higher HRTs. Hence, during regression analysis, such low values of R^2 were obtained in these months.

Biomass granulation and settling

The inoculum used to start up the reactor was flocculent in nature rather than granular. Specific density of the sludge collected from the UASB reactor on 200^{th} day was 40.80 g VSS/L and that for the inoculum sludge it was 8 g VSS/L. Specific gravity of the sludge from UASB reactor was 1.04 as compared to 1.023 for inoculum sludge. Particle size distribution of the inoculum at the start of the experiments and at day 200, expressed in the percentage of the biomass volume represented by the granules is shown in Figure 3. After 200 days of operation around 5.63% of the sludge had a diameter of 1.0 mm, while 3.53% of the sludge had a diameter more than 1.0 mm. In comparison the inoculum sludge had 2.82% of particles of diameter more than 1 mm. Particles of diameter greater than 3 mm had a settling velocity above 150 m/h which concludes that they might contain inert precursor material and not completely consisting of biomass sludge granules. While size of granular sludge has been widely reported to range from 0.5 mm to 5 mm, some researchers have reported sludge of size 0.16 mm or less as granules (Bhunia & Ghangrekar, 2007). Based on Reynold's number, Bhunia and Ghangrekar (2007) calculated the minimum size of granules as 0.34 mm which makes around 63.47% of the sludge inside the UASB reactor after 200 days of operation as granular sludge. For the rest of the particles with size less than 0.34 mm, they can be regarded as pellets, which are aggregates with a more dense structure than flocs, which constituted around 60% fraction in the basic inoculum sludge (Bhunia & Ghangrekar, 2007); whereas this fraction was only 34% after 200 days of operation. To the best of the knowledge of the authors such percentage of granulation has not been reported while treating sewage in full scale UASB reactor.

SVI less than 20 mL/g is reported for granular sludge, whereas for flocculent sludge the SVI ranges between 20 and 40 mL/g (Bhunia & Ghangrekar, 2008a). Equal values of SVI_5 and SVI_{30} indicate good sedimentation properties (Jin et al., 2013; Tang et al., 2011). Similar phenomena were observed in the present study with SVI_5 and SVI_{30} being 31.15 mL/g and 28.2 mL/g, respectively, after 200 days of operation of the pilot reactor. The SVI_{30} of the inoculum sludge was 34.3 mL/g. It is worthy to note that the sludge samples used for determination of size distribution and settling velocity were collected from the reactor at a height of 200 cm from the bottom. Thus, the sludge at the bottom of sludge bed are expected to have even larger sizes and higher settling velocities (Li & Sung, 2015).

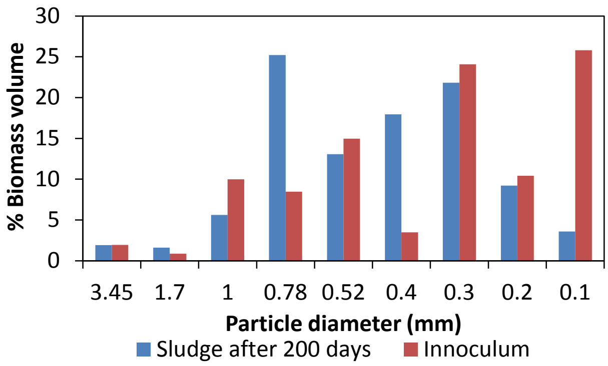

Figure 3: Particle size distribution of inoculum sludge and sludge collected from UASB reactor

Biomass granulation inside UASB reactors under favourable environmental conditions is mostly governed by the inoculum concentration and mixing in the sludge bed. The mixing is mainly induced by the upward movement of produced biogas and upflow velocity of wastewater in the reactor. A dimensionless number biomass granulation index (BGI) and granulation index (GI) was developed by Bhunia and Ghangrekar (2009) and Bhunia and Ghangrekar (2008b), respectively to define favourable mixing conditions in the sludge bed of UASB reactor and that was correlated with percentage granulation. Bhunia and Ghangrekar (2009) concluded that good granular sludge (percentage of granules more than 50%, w/w) can be developed in UASB reactor if BGI is maintained in the range of 240 to 560. To obtain proper granulation in UASB reactors (percentage granules greater than 50%, w/w), resulting in higher COD removal efficiency, Bhunia and Ghangrekar (2008b) recommended to maintain GI values in the range of 15,000–57,000. For the present study, when the BGI was calculated initially with inoculum sludge concentration of 8 g/L, BGI was 185; however, with continued operation and increase in sludge concentration within the reactor the BGI value increased to an average of 280 and a maximum of 380, indicating a 50 – 60% possibility of granulation (Bhunia & Ghangrekar, 2009) which is also evident from the settling velocity test. However, the GI values were not in the range for favourable granulation in the present study.

Biomass characterization

VSS/SS ratio of sludge indicates the viable micro-organisms present and percentage of inert matters content in the sludge. Specific gravity of granules is predominantly governed by the combined effects of percentage of inert matters content and density of cells (number of cells). Increase in VSS/SS ratio, indicates decrease in inert material content of sludge. Bhunia and Ghangrekar (2007) reported an optimum VSS/SS ratio of 0.5 for granular sludge of 1.5 mm size. The average VSS/SS ratio in the sludge collected from the bottom of the pilot UASB reactor was 0.56 and it was above 0.5 throughout the entire range of operation, with the ratio being above 0.6 for the winter months. Bhunia and Ghangrekar (2007) also observed a decrease in SMA of the sludge with increase in VSS/SS ratio, which is evidenced by the lower biogas production in the winter months from the reactor.

Extracellular polymeric substances (EPS) can mediate both cohesion and adhesion of cells, and play a crucial role in maintaining structural integrity of microbial matrix (Liu et al., 2003). Total EPS content of the sludge collected from the bottom of the UASB reactor was 12.94 mg/g VSS. Besides EPS content, their distribution in different fractions namely slime EPS (S-EPS), loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS), is important as well to understand bacterial cell stability (Figure 4). The presence of TB-EPS provides a shield to bacterial cells and it is often considered as the ‘‘skeleton” of sludge, mediating both cohesion and adhesion of cells (Lu et al., 2015; Zhen et al., 2013). On the other hand higher concentration of S-EPS and LB-EPS gives sludge a porous and fluffy structure with higher amount of bound water inside (Bergmans et al., 2014). The ratio of proteins and carbohydrates in sludge is used to determine its strength, stability and settling ability, with a higher ratio indicating low strength granules with bad settling properties and poor stability (Chen et al., 2015; Lu et al., 2015; Tang et al., 2011; Xing et al., 2015). Similar phenomenon was also observed in our study. The PN/PS ratio of the raw sludge was around 2.13; whereas that for the sludge collected on day 200 from the UASB reactor was 0.94. The PN/PS ratio of floating sludge was significantly higher about 3.36 (Figure 4). The increase in PN content was observed to be much less than the increase in PS content in the sludge inside the UASB thus leading to the formation of high strength granules.

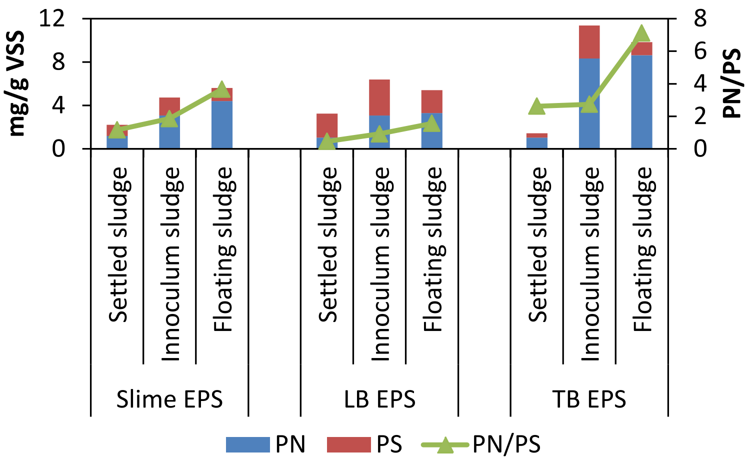

Figure 4: PN and PS content in inoculum, settled and floating sludge

Strength of granules was measured as integrity coefficient, which should be less than 20%, as reported by Ghangrekar et al. (1996), where strength of granules is inversely proportional to the value of integrity coefficient. The highest strength of settled sludge, indicated by lowest integrity coefficient as 3.74% was developed for the sludge collected from the UASB reactor.

Performance of HRAP

As evident from Figure 5, start-up of the algal pond comprised of two steps based on the ammonium removal performance: lag phase (1 – 50 days) and propagation phase (still continuing). Lag phase was characterized by sharp variations in effluent ammonium concentrations and ammonium removal efficiency (Figure 5). During this lag period a reduction of ammonium was observed, but only after one month of operation, before which an increase of ammonium ion was detected. This may be due to organic hindrance or self-degradation of nutrients in wastewater thus making it unavailable to species, hence leading to less chlorophyll concentration in wastewater (Kiran et al., 2014). After reaching steady ammonia removal increased to 85.1 ± 2.4%. With influent ammonia nitrogen concentrations of 20 ± 3 mg/L the average effluent ammonia nitrogen concentration was 3 ± 1 mg/L. Though during lag phase, there was very little biomass built up or nitrogen removal; however there was a stable phosphate removal starting from the initial days which reached to a maximum of 91 ± 1%. A final effluent total COD of around 50 ± 6 mg/L could be obtained after treatment with HRAP. There was a 4 log scale pathogen removal after treatment with HRAP with MPN of the final effluent being less than 1000/100 ml, which is within acceptable standards for surface irrigation (CPCB, 1993).

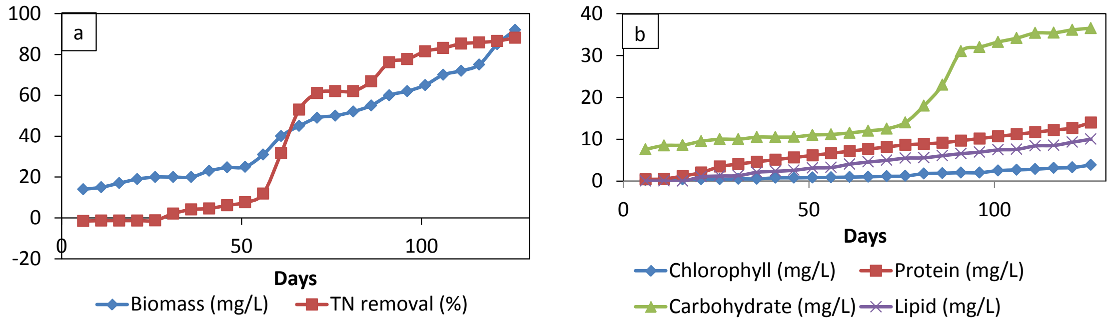

Figure 5: Variation of (a) algal biomass and TN removal efficiency, (b) biochemical parameters of algae with time

Biochemical analysis of microalgae was also done to observe the changes in terms of proteins, carbohydrates and lipids concentration in the presence of wastewater. Accumulation of these has been found to be increasing with time. High levels of protein in the later stages of growth support the decrease in levels of nitrogen or rapid uptake of nutrients for metabolic activity. Decreasing levels of nitrogen content also plays important role in the production of lipids (Kiran et al., 2014).

CONCLUSIONS

Wastewater contains many organic and inorganic nutrients, which are discharged into water streams causing environmental pollution and health hazards. UASB reactor successfully gave more than 70% COD removal with biomass granulation. Utilization of nutrients present in the treated sewage for the growth of microalgal species will not only control eutrophication but will also help in sustainable energy development. The findings of this study suggest that sewage wastewater can be directly used for mass cultivation of microalgae without requiring additional nutrient supplements. The effluent of the algal pond can be directly reused for surface irrigation of non-food crops.

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