Development of an ecologically sustainable wastewater treatment system

Lokendra Kumar, Rajiv Ranjan and P. C. Sabumon

ABSTRACT

The present study aimed mainly for the development of a wastewater treatment system incorporating enhanced primary treatment, anaerobic digestion of coagulated organics, biofilm aerobic process for the removal of soluble organics and disinfection of treated water. An attempt was also made to study the reuse potential of treated water for irrigation and use of digested sludge as soil conditioner by growing marigold plants. Ferric chloride dose of 30 mg/l was found to be the optimum dose for enhanced primary treatment with removals of COD and BOD to the extent of 60% and 77%, respectively. Efficient anaerobic digestion of ferric coagulated sludge was performed at 7 days hydraulic retention time (HRT). Upflow aerobic fixed film reactor (UAFFR) was very efficient in removals of COD/BOD in the organic loading rate (OLR) range of 0.25 to 3 kg COD/m^3/day with COD and BOD removals in the range 65–90 and 82–96, repectively. Photo-oxidation followed by disinfection saved 50% of chlorine dose required for disinfection of treated effluent and treated water was found to be suitable for irrigation. The result also indicated that anaerobically digested sludge may be an excellent soil conditioner. From the results of this study, it is possible to conclude that the developed wastewater treatment system is an attractive ecologically sustainable alternative for sewage treatment from institutional/industrial/residential campuses.

Key words | ecologically sustainable, enhanced primary treatment, fixed film reactor, organic loading rate, photo-oxidation, wastewater

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INTRODUCTION

In the recent past, the environmental regulations have undergone a vast change. As a result, conventional treatment technologies have been further refined and new technologies for the wastewater treatment is in implementation and or in development stage to meet increasingly more stringent water quality criteria.

The present challenge is to meet these new requirements in a way that is both environmentally sustainable and cost effective. In order to achieve environmentally sustainable wastewater treatment, a closed-loop treatment system is appropriate. Many present wastewater treatment systems are a "disposal-based linear system". The traditional linear treatment systems must be transformed into the cyclical treatment to promote the conservation of water and nutrient resources (Rose 1999) and there by increase the scope of sustainability of wastewater treatment.

Generally, wastewaters contain soluble and insoluble organic substances along with other contaminants. The insoluble organics comprise settlable solids and non settlable solids. In conventional wastewater treatment, the primary treatment removes the large and settlable solids by physical separation to an extent of 60% (BOD removal of 30–35%) and the rest of settlable solids and colloidal solids enter in to aerobic biological treatment process

doi: 10.2166/wst.2008.341

(Metcalf & Eddy 2001). The degradation of these colloids and suspended solids in aerobic system takes more time at an extreme level of energy input.

There can be a better option of treating wastewater by an enhanced primary treatment with removal of colloids and settlable solids by chemical coagulation using ferric chloride ($FeCl_3$) as a coagulant (Aiyuk *et al.* 2004). The concentrated coagulated organics can be separated easily and treated anaerobically with lot of advantages. The supernatant of the primary treatment, which contains mainly soluble pollutants, can be treated in aerobic fixed film reactor in an efficient and cost effective way. The present study was aimed mainly for the development of an ecologically sustainable wastewater treatment system incorporating enhanced primary treatment, anaerobic digestion of coagulated organics and biofilm aerobic process for the removal of soluble organic fraction. The products or byproducts of treatment could be recovered and reused to make the treatment option ecologically sustainable.

MATERIALS AND METHODS

The process flow scheme used in this study is shown in Figure 1. The wastewater treatment was carried out as per process flow scheme using sewage taken from equalization tank of VIT's sewage treatment plant (www.vit.ac.in).

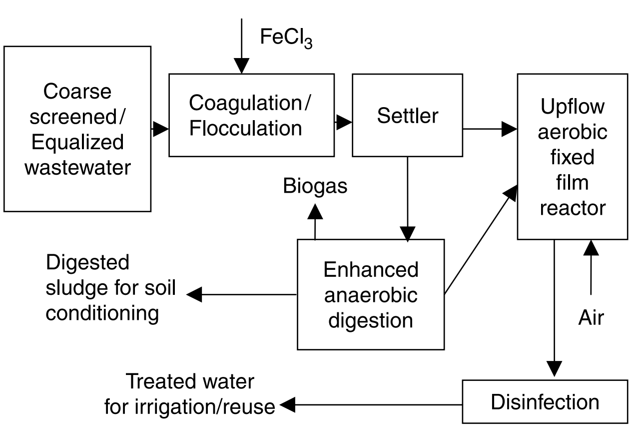

Figure 1 | Process flow diagram of ecologically sustainable wastewater treatment system.

Enhanced primary treatment

The equalized sewage was collected in a plastic bucket of 50 L capacity and stirred rapidly for one minute after the addition of optimum coagulant dose of 30 mg/l of $FeCl_3$. The optimum coagulant dose was determined by Jar testing (using 1 L capacity jars) with different coagulant doses (i.e. 10, 20, 30, 40, 50 and 60 mg/l). The coagulant dose (30 mg/l of $FeCl_3$) which gave maximum removals of COD/BOD/S.S and minimum sludge volume after 30 minutes settling was fixed as optimum coagulant dose. After rapid mixing of coagulant, the contents in bucket were slowly mixed (manually using coconut tree leafs as paddle) for 20 minutes and allowed to settle for 30 minutes. Then the supernatant was transferred to feed vessel of upflow aerobic fixed film reactor (UAFFR) and settled sludge was transferred to anaerobic digester.

Operation of UAFFR

The reactor (UAFFR) of 10 L capacity was made of 6 mm thick acrylic sheet having size of 120 cm × 10 cm × 10 cm. PVC rings (1.9 cm outer diameter and 2 cm height) having a porosity of 90% and bulk density of 154 kg/m^3 were used as non reactive media for microbial attachment. The reactor was started up by recycling of primary treated effluent for biofilm growth over the PVC rings for two weeks. Peristaltic pump (Miclins, India) was used for feeding wastewater to UAFFR. The compressed air was supplied to the bottom of reactor through a diffuser stone. The UAFFR was started in continuous operation at 24 h HRT and HRT further reduced to 12 h, 6 h, 3 h, 1.5 h, and 1 h after stabilized operation in each HRT. The dissolve oxygen was maintained in the range of 2 to 4 mg/l and temperature varied from 26°C to 31°C during the study over a period of 4 months.

Anaerobic digester

The sludge generated from the enhanced primary treatment was treated anaerobically by using anaerobic digester. A 25 L capacity transparent plastic vessel with biogas collection arrangement (by liquid displacement method) was used as anaerobic digester. The start-up of anaerobic digester was done by seeding 10 L anaerobically digested cow dung (having volatile suspended solids of 92.7 g/l) and 1.5 L of settled sludge from primary treatment was added daily. After 10 days, supernatant of 1.5 L was taken out daily for feeding to aerobic fixed film reactor along with supernatant from enhanced primary treatment. After stabilization of the process, HRT of operation was reduced from 10 days to 7 days.

Disinfection of UAFFR effluent by chlorination

Effluent from UAFFR was taken in eight numbers of BOD bottles with 200 ml volume in each bottle. Different chlorine doses of 10, 20, 30, 40, 50, 60, 80 and 100 mg/l were added to each bottle. The selected dose was added from the stock solution of chlorine after determining its strength. Closed bottles were shaken in an orbital shaker (Remi, India) at 120 rpm for 30 min. After 30 min., the samples from each bottle were analyzed for residual chlorine, pH, and bacterial count. A blank was also run in similar conditions without any Cl_2 dose.

Disinfection of UAFFR effluent by photo-oxidation followed by chlorination

Effluent from UAFFR was taken in a clean bucket for the photo-oxidation at different depth of water (10, 15 and 25 cm). Effluents were exposed to the sunlight for 3 h (Indian standard time 11 h to 14 h where intensity of sunlight was maximum at Vellore) and samples were drawn for bacterial count. After photo-oxidation, samples were subjected to chlorination at different chlorine doses of 5, 10, 20, 30, 40 and 50 mg/l in the same way as described in previous section.

Reuse of treated water

To study the reuse potential of treated water for irrigation, marigold plant saplings obtained from VIT's nursery were used in field conditions. Marigold was selected because it was fit for the study season (January to April) and its life is 3 to 4 months. Marigold is one of the commercial flowers in India used for decoration in various occasions. There was no fertilizer used during analysis period i.e. from germination to end of the plant life. Plant saplings having same features were transferred to four different pots for the reuse studies. The red soil was used for the growing of the plant. Different types of water were used for the irrigation of the marigold plant sapling in pots. Tap water (Control S1), treated effluent from UAFFR (S2), treated effluent from UAFFR after chlorination (S3), and treated effluent from UAFFR after photo oxidation followed chlorination (S4) were used for irrigation. Morning and evening 300 ml of designated water was irrigated in each set of plants. The growth of plant was studied by the measuring the different parameter such as length of plant, root length, shoot length, stem perimeter, number of leaves, area of leaves, number of flowers, and chlorophyll content.

Digested sludge for soil conditioning

One litre of anaerobic digested sludge was mixed with 3.5 to 4 kg of red soil and marigold sapling planted in pot filled with conditioned soil. The growth of plant (S5) was compared with growth of the plant without soil conditioning. Treated water from the UAFFR was used to irrigate the plants.

Analytical methods:

All physico-chemical analysis was carried out as per *Standard Methods* (1998). Volatile fatty acids (VFA) and bicarbonate alkalinity of anaerobically treated effluent was determined as per procedure developed by Anderson & Yang (1992). The composition of CH_4 and CO_2 in biogas was determined by using Orsat apparatus. A measured volume of biogas was scrubbed first through a solution of 30% potassium hydroxide (KOH) to remove CO_2. After scrubbing, the volume of gas remained was considered as CH_4 (by assuming biogas composed of only CH_4 and CO_2) and percentage of CH_4 was calculated. Chlorophyll content of marigold plant leaves was determined by extraction in 80% acetone (10 mg plant material extracted in 1 ml of acetone) and absorption of extract at 663 nm and 645 nm were measured in a spectrophotometer. Using the absorption coefficients, the amount of chlorophyll was calculated using the following equations:

$$\text{mg chlorophyll } a/\text{g tissue} = 12.7(A_{663}) - 2.69(A_{645})\text{V}/(1000\text{W})$$

$$\text{mg chlorophyll } b/\text{g tissue} = 22.9(A_{645}) - 4.68(A_{663})\text{V}/(1000\text{W})$$

$$\text{mg Total chlorophyll/g tissue} = 20.2(A_{645}) + 8.02(A_{663})\text{V}/(1000\text{W})$$

where A = absorbance at specific wavelengths, V = final volume of chlorophyll extract in 80% acetone, W = fresh weight of tissue extracted.

RESULTS AND DISCUSSION

Characteristics of VIT's sewage

The characteristics of sewage at VIT's wastewater treatment plant were pH (7.4–7.6), suspended solids (316–500 mg/l), COD (256–640 mg/l), BOD (120–240 mg/l) and bacterial count ($16.5-19.5 \times 10^6$ CFU/ml). The composition of sewage varies from place to place because it depends on habits of population. From the characteristics of VIT's sewage, it was found all parameter values were in the range of medium sewage (Garg 1998).

Enhanced primary treatment

The enhanced primary treatment was achieved by adding $FeCl_3$ as a coagulant to coagulate the colloidal and/or suspended solids present in the sewage. Figure 2 shows the results of primary treatment of wastewater with different doses of $FeCl_3$ as coagulant. From the results it is evident that $FeCl_3$ dose of 30 mg/l gave better removal of COD (60%) and BOD (77%). Fenton's reagent dose of 30 mg/l during coagulation-flocculation of combined wastewater gave a comparable COD removal of 57% (Duran *et al.* 2003). Aiyuk *et al.* (2004) reported improved removal of an average 73% removal of COD when domestic wastewater coagulated with $FeCl_3$ and flocculated by addition of an anionic organic flocculent. The percentage removals of COD and BOD in this study without $FeCl_3$ addition were 28.4 and 38.6, respectively. The results showed enhanced removal of COD/BOD in primary treatment as a result of

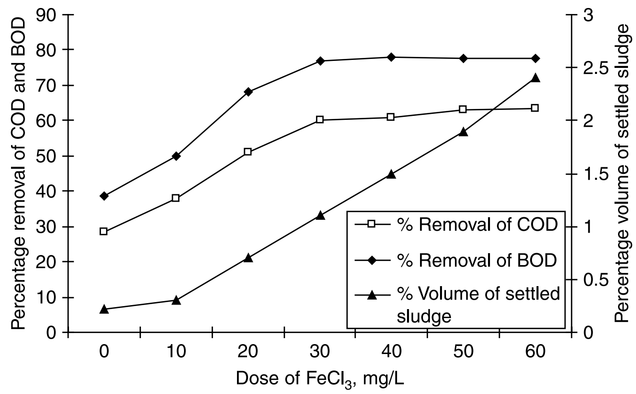

Figure 2 | Results of enhanced primary treatment.

$FeCl_3$ addition as a coagulant. There was increased removals of suspended solids and turbidity at optimum coagulant dose. It was also observed that percentage volume of settled sludge increased with increase in dose of $FeCl_3$.

Enhanced anaerobic digestion

Figure 3 shows the weekly performance of 25 L capacity anaerobic digester. From Figure 3, it was observed that the anaerobic digestion of sludge from enhanced primary treatment improved with time of operation. After 8 weeks of operation, the COD of anaerobic effluent was below 100 mg/l. The biogas production was varied and might be due to variation of the feed COD to the digester. The methane in the biogas was varied from 50 to 60%. pH (6.9–7.4), VFA (22–110 mg/l), bicarbonate alkalinity (600–1,700 mg/l) and VFA/Bicarbonate alkalinity ratio were within the limits of safe operation of anaerobic

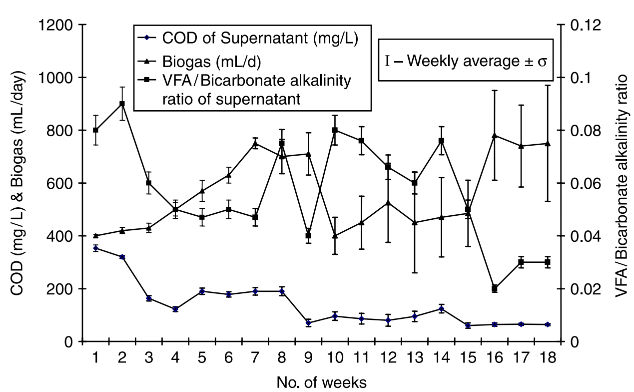

Figure 3 | Performance of anaerobic digester.

digester. The low ratio of VFA/Alkalinity (<0.3) indicates that anaerobic digestion is effective in reactor (Yacob *et al.* 2006; Risk *et al.* 2007). The temperature of anaerobic digester varied from 34°C to 39°C. Methane formers grow best in mesophilic optimal temperature range between 35 to 40°C (Grasius *et al.* 1997). Sulphide and total iron in anaerobic effluent were varied from 24 to 29 mg/l and 0.5 to 1 mg/l respectively. It was observed that percentage volatile fraction of digested sludge was decreased with time of operation from initial values of 65.2–68.4 to lower values of 22.8–25.6 at end of study. The digested sludge was having good settling and dewatering properties. From the optimization study of anaerobic digestion carried out in a 2 L aspiratory bottle, it was observed that primary sludge was hydrolyzed and anaerobically oxidized within a day time. The results obtained in this study indicated that enhanced anaerobic digestion of iron coagulated primary sludge is possible.

Performance of UAFFR

Figure 4 shows the performance of UAFFR with increase of organic loading rate (OLR). The UAFFR was started at 24 h HRT and further reduced to 12, 6, 3, 1.5, and 1 h HRT in corresponds to increase of OLR. After 2 weeks of operation, the treated effluent COD was below 100 mg/l during the steady state of operation which met the discharge norms to surface waters as per Central Pollution Control Board (CPCB) in India. The percent removal of COD in the UAFFR varied from 65 to 90 during steady state operation. The treated effluent BOD was less than 10 mg/l (meeting CPCB discharge standard) and maintained 82–96% reduction in BOD at steady state of operation. The performance of reactor affected at above 3 kg COD/m^3/day. However, the COD of effluent remained less than 100 mg/l at higher OLR of 4 kg COD/m^3/day. The percentage removal of suspended solids in the UAFFR varied from 72–86% with concentration less than 100 mg/l. Whenever there was change of OLR, the reactor performance showed a decreased performance and regained to normal performance within short time. At steady state of operation effluent from UAFFR was having pH (7.1–7.9), Turbidity (4–6 NTU), suspended solids (20–40 mg/l), BOD (6–30 mg/l), COD (32–64 mg/l), NH_4—N (10–40 mg/l), TKN (10–40 mg/l) and phosphorus 10–25 mg/l. McDowell & Hubbell (2001) reported that submerged fixed film reactor technology can be employed for effective wastewater treatment with high biomass retention.

Disinfection of UAFFR effluent

The treated water from UAFFR contained bacteria in the order of 10^6 CFU/ml. Before reuse of treated water, disinfection of the pathogen is necessary because it can affect human health. So UAFFR effluent was studied for disinfection of pathogens by break point chlorination and photo-oxidation followed by chlorination.

Figure 5 shows break point chlorination of UAFFR effluent. At chlorine dose of 40 mg/l breakpoint was achieved and treated water was free from any bacterial count. The residual pH was varying from 7.9 to 8.61. After breakpoint chlorination, treated water was suitable for irrigation (WHO 1989). Mujeriego *et al.* (2000) reported that wastewater treated by the conventional activated sludge

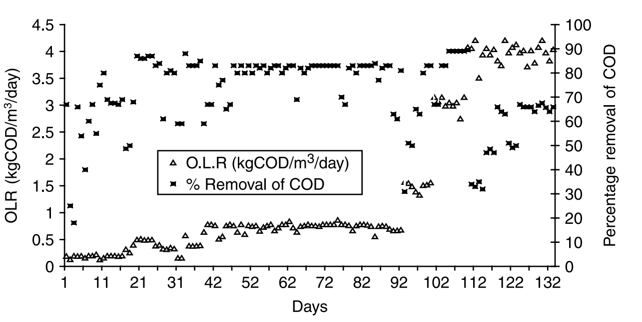

Figure 4 | Performance of UAFFR with varying organic loading rate (OLR).

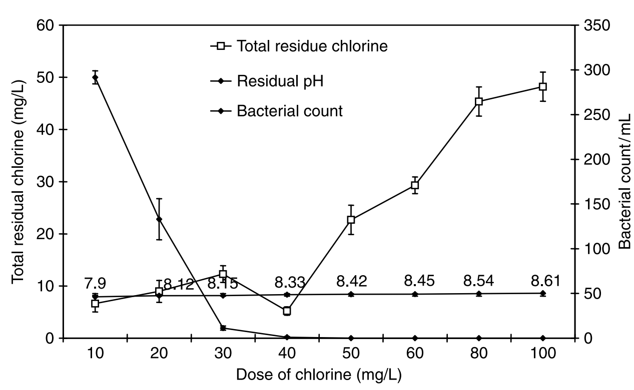

Figure 5 | Break point chlorination of UAFFR effluent.

process needs 25 to 45 mg Cl_2/l for chlorination and after chlorination it had fecal coliforms and fecal streptococci concentrations lower than 100 CFU/100 ml. The pH varied up to 9.00 in their study. The results of present study were comparable with their results.

As a result of photo-oxidation of treated water there was a reduction of 10^3 CFU/ml in bacterial count at all depth of water studied. The breakpoint was achieved at a chlorine dose of 20 mg/l with no bacterial count after 30 min. contact time. The residual chlorine at breakpoint was 2.1 mg/l. The results show that after photo-oxidation chlorine demand was decreased by a factor of 2. Therefore, photo-oxidation followed by chlorination appears to be an alternative economical method of disinfection of treated wastewater.

Reuse of treated water

The growth parameters of all marigold plants were good compared to the control plant (S1). However, it was observed that chlorinated water irrigated sample (S3) was having adverse effect on leaf surface area and chlorophyll content compared to soil conditioned plant (S5). The chlorophyll content in latter case was 38% more. By comparing UAFFR treated irrigated plant (S2) with soil conditioned plant (S6), all the growth parameters of soil conditioned plant showed substantially better values. This result indicated that anaerobically digested sludge may be an excellent soil conditioner. Among the treated water irrigated plants (S2 to S4), S3 and S4 did not show much difference in their growth patterns. However, photo-oxidation following chlorination is better for water reuse because of its economy and safety for reuse application.

CONCLUSION

From the results of this study, it is possible to conclude that the developed wastewater treatment system is an attractive ecologically sustainable alternative for sewage treatment from institutional/industrial/residential campuses. The treatment concept can also be employed for decentralized treatment of municipal wastewater. The advantages of the developed system may be of less land area requirement, less energy requirement and reuse/recovery potential of products/byproducts.

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