An innovative approach to minimize excess sludge production in sewage treatment using integrated bioreactors

Mahesh Mannacharaju, Prabhakaran Natarajan, Arivizhivendhan Kannan Villalan, Madasamy Jothiswari, Swarnalatha Somasundaram, Sekaran Ganesan

Department of Environmental Science and Engineering, CSIR – Central Leather Research Institute (CLRI), Adyar, Chennai 20, India

ARTICLE INFO

Article history:
Received 27 April 2017
Revised 21 July 2017
Accepted 31 July 2017
Available online 2 August 2017

Keywords:
Sequential oxic and anoxic bioreactor (SOABR)
FICCO reactor
Domestic wastewater
Immobilized cell reactor

ABSTRACT

The present investigation deals with an application of integrated sequential oxic and anoxic bioreactor (SOABR) and fluidized immobilized cell carbon oxidation (FICCO) reactor for the treatment of domestic wastewater with minimum sludge generation. The performance of integrated SOABR-FICCO system was evaluated on treating the domestic wastewater at hydraulic retention time (HRT) of 3 hr and 6 hr for 120 days at organic loading rate (OLR) of 191 ± 31 mg/(L·hr). The influent wastewater was characterized by chemical oxygen demand (COD) 573 ± 93 mg/L; biochemical oxygen demand (BOD5) 197 ± 35 mg/L and total suspended solids (TSS) 450 ± 136 mg/L. The integrated SOABR-FICCO reactors have established a significant removal of COD by 94% ± 1%, BOD5 by 95% ± 0.6% and TSS by 95% ± 4% with treated domestic wastewater characteristics COD 33 ± 5 mg/L; BOD5 9 ± 0.8 mg/L and TSS 17 ± 9 mg/L under continuous mode of operation for 120 days. The mass of dry sludge generated from SOABR-FICCO system was 22.9 g/m3. The sludge volume index of sludge formed in the SOABR reactor was 32 mL/g and in FICCO reactor it was 46 mL/g. The sludge formed in SOABR and FICCO reactor was characterized by TGA, DSC and SEM analysis. Overall, the results demonstrated that the integrated SOABR-FICCO reactors substantially removed the pollution parameters from domestic wastewater with minimum sludge production.

© 2017 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V.

Keywords:
Sequential oxic and anoxic bioreactor (SOABR)
FICCO reactor
Domestic wastewater
Immobilized cell reactor

Introduction

The environmental management on liquid and solid wastes generated due to human activities has become increasingly critical due to increase in worldwide population growth. The aerobic biological process in conventional wastewater treatment system is the major unit operation followed for the treatment of domestic wastewater. However, the aerobic biological treatment process generates huge quantity of sludge owing to high concentration of suspended solids and biodegradable organic compounds present in the wastewater. Hence, anaerobic system has been considered to reduce sludge production and thereby to eliminate sludge disposal problems (Vorosmarty et al., 2010; Mungray and Patel, 2011; Pontes and De Lemos Chernicharo, 2011). Many integrated anaerobic and aerobic biological treatment technologies have been developed for the treatment of domestic wastewater (Watanabe et al., 2016). The upflow anaerobic sludge blanket (UASB) system was developed for the effective treatment of domestic wastewater. Although UASB treatment process is widely practiced, it has certain disadvantages such as high operation cost and extensive foot print requirement and...
applicability only to selective industrial wastewater (Buntner et al., 2013; Abbasi and Abbasi, 2012; Luciano et al., 2012; Wang et al., 2014). The global standards, made stringent on disposal of wastewater and solid waste (Verlicchi et al., 2011), demand the development of more efficient treatment technologies that have features such as minimum foot print requirement, less electric energy consumption and minimum sludge generation. Researchers have developed hybrid UASB reactor, membrane bioreactor (Lin et al., 2012; Buntner et al., 2013; Qiu et al., 2013; Wang et al., 2014), aerated bio filter (Chung et al., 2016), sequential batch reactor (Moawad et al., 2009), down-flow hanging system (Tandukar et al., 2007), Chemocatotrophic activated carbon oxidation system (Sekaran et al., 2007) etc. for the treatment of wastewater. Despite these technologies address efficient removal of organic pollutants and they generate huge quantity of sludge. There are reports on biofilm reactors to reduce the sludge production and low operational cost for treatment of sewage (Tawfik et al., 2010, 2012; Khan et al., 2015; Chatterjee et al., 2016; Deng et al., 2016). Biofilm reactor technology has been regarded as the simplest in design, flexible in operation and compact in space requirement for the treatment of wastewater. It served as an added advantage on freely moving carriers in the reactor to support biofilm development (Ødegaard et al., 2000; Leyva-Díaz et al., 2013). The design and operation of sequential oxic and anoxic zones in biological reactor improved the nutrients removal and anoxic zone facilitated the supporting area for sludge digestion (Wei et al., 2013). Design aspect of the sequential oxic and anoxic biofilm reactor with plastic material as carrier matrix for biofilm growth forms the novel part of the present investigation.

The biofilm moving bed reactors are known to produce less quantity of sludge than in activated sludge processes because of the longer food chains in biofilms under continuous operating conditions (Zhang et al., 2017; Leyva-Díaz et al., 2013; Qi et al., 2014). The sequential oxic and anoxic biofilm reactor (SOABR) is non cloggable under continuous mode of operation, it does not need backwashing and it has low head loss with high specific biofilm surface area. The biofilm attached carrier matrices move under constant motion throughout the entire volume of the reactor and the sloughed biomass from the carrier matrices is considered to be the sludge (Qi et al., 2012; Leyva-Díaz et al., 2013). The nutrient removal in SOABR was rate limitation process. So, the fluidized immobilized cell carbon oxidation (FICCO) reactor with hydraulic retention time (HRT) of 6 hr was operated sequentially after SOABR for the efficient removal of organics by immobilized microbial mass in the carbon matrix and microalgae biofilm in plastic carrier media. The effective removal of nutrients in sewage was possible through microalgae biofilm (Ruiz-Marín et al., 2010; Gao et al., 2015). The operation of SOABR followed by FICCO reactors have high sludge retention time with minimum sludge generation.

The disposal of the sludge generated from conventional treatment process becomes a confronting environmental issue to the industries. Hence, a technology for the efficient removal of organics with minimum sludge production is the hour of need. Hence, the present investigation was focused on the treatment of domestic wastewater using integrated SOABR with FICCO reactor to minimize sludge generation.

### 1. Experimental methods

#### 1.1. Reactor design

A rectangular shaped bench top laboratory-scale SOABR was designed and fabricated using transparent acrylic sheets. The SOABR consists of three compartments of equal size (24 cm (L) × 24 cm (b) × 36 cm (H)) with a capacity of 16 L which were connected internally in series as shown in Fig. 1. The bottom of the reactor was sloped at 8° with the base to increase the efficiency of flow dynamics of suspended particles present in the wastewater. The carrier matrices (cylindrical shaped packing material, diameter 21 mm) were filled by about 20% volume of the reactor (working volume fraction) for the growth of biofilm.

The modified FICCO reactor (volume, 32 L) was designed and fabricated with some modifications as reported by Karthikeyan et al. (2015). The FICCO reactor contains a triangular septum and the zone below this is kept under fluidization to hydrolyse the organic chemicals, and the zone placed above the triangular septum contains a hopper vessel with an aperture to facilitate wastewater to enter. The hopper zone contains packing carrier matrices to promote microalgae biofilm growth using the nutrients from the treated wastewater in the reactor.

The schematic process flow diagram of integrated SOABR with FICCO (SOABR–FICCO) reactor is shown in Fig. 1. The domestic wastewater collected from the sewage collection tank located in a residential colony, Central Leather Research Institute, Chennai (India) was applied twice in a day. The study was performed for 120 days with HRT of 3 hr in SOABR and 6 hr in FICCO reactor.

#### 1.2. Physico-chemical analysis of the wastewater

The samples were collected at regular time intervals for the analyses of turbidity @ $\lambda_{600}$ nm, chemical oxygen demand (COD), bio-chemical oxygen demand (BOD$_5$), total solids (TS), total dissolved solids (TDS) and total suspended solids (TSS) in accordance with the methods summarized in the standard methods for the analysis of wastewater (APHA-standard methods, 1998). Total solids of the wastewater sample was determined by weighing the mixed liquor samples collected from the reactor before and after drying at 105°C. The biomass concentration in terms of the mixed liquor volatile suspended solid (MLVSS) was analysed by loss on ignition at 600°C for 2 hr. The sludge volume index (SVI) is considered as the volume of (mL) unit weight of activated sludge that settled in 30 min (APHA-standard methods, 1998).

$$\text{SVI} = \frac{30}{H_s}$$

where $H_s$ is the height of sludge in mL after 30 min of settling, $A_0$ is the initial height of the slurry in L and $A_0$ (mg/L) is the initial mixed liquor suspended solid concentration in the slurry.

#### 1.3. TGA and DSC analyses for SOABR and FICCO sludge

Required quantity (8–10 mg) of dry sludge from SOABR or FICCO reactor after continuous mode of operation was loaded in a platinum TGA pan and thermo gravimetric analysis (TGA)
was carried out under pure nitrogen atmosphere, from 30 to 800°C at a temperature gradient of 10°C/min. The thermogram was routinely recorded as duplicates using TGA Universal V4.4A (TA instruments). Differential scanning colorimetry (DSC) analysis was carried out by loading the required quantity (8–10 mg) of dry sludge from SOABR or FICCO reactor after continuous operation. DSC analysis was carried out under reduced nitrogen atmosphere from 30 to 300°C at a temperature gradient of 10°C/min for the sludge samples loaded in aluminium DSC pan. The scans were routinely recorded as duplicates using DSC Q200 (V23.10 Build 79, TA instruments).

1.4. Scanning electron microscope analysis of biofilm

The carrier plastic material and nanoporous activated carbon (NPAC) samples were collected at the start-up period and at the end of the experiment for scanning electron microscopy (SEM) analysis. The biofilm attached onto the carrier media and NPAC were fixed with 2% glutaraldehyde and phosphate buffer (0.1 mol/L at pH 7.5) and cured for 24 hr at 4°C. Subsequently, the samples were washed three times with phosphate buffer solution (0.1 mol/L) for 10 min. Finally, the samples were dehydrated sequentially with ethanol of 10, 20, 40, 60, 80, and 100% (V/V) and dried using carbon dioxide at room temperature. The samples were coated with gold by the gold sputtering device for the clear visibility of the surface morphology. The biofilm microstructures were captured using Leo-Jeol supplied SEM with a magnification of 2500–10,000.

1.5. Effect of raw and treated sewage on seed germination

The seed germination studies were carried out using Whatman filter paper method in accordance with the procedure reported by International Seed Testing Association (1996). The seeds of Solanum lycopersicum were surface sterilized with mercuric chloride solution of 1% (W/V) for 2 to 3 min and washed with distilled water. Ten seeds were sowed randomly at some approximate equal distance between the seeds on each pre-sterilized petri plate lined with Whatman filter paper. A known volume (10 mL) of untreated or treated sewage samples were sprinkled onto petri plate. The petri plates added with deionized water were served as control. The seed germination index was calculated based on the method described by Abdul-Baki and Anderson (1973).

2. Results and discussion

The initial characteristics of raw sewage are shown in Table 1. The treatment efficiency of integrated SOABR-FICCO system was evaluated based on the pollution parameters such as turbidity, COD, BOD₅, total solids, total dissolved solids and total suspended solids under continuous mode of operation for 120 days at room temperature (Fig. 2). The initial start-up period for the development of biofilm was 20 days. The data acquisition were collected from 20th day onwards twice/thrice a week. The domestic wastewater was continuously fed to SOABR reactor at organic loading rate (OLR) of 191 ± 31 mg/(L·hr) and sequently to FICCO reactor.
2.1. Performance of turbidity and total coliform removal by integrated SOABR and FICCO reactors

The turbidity removal after passing through SOABR and FICCO reactors are shown in Fig. 2a. The maximum optical absorption by wastewater sample measured at λ600 nm after 120 days operation in SOABR and FICCO reactors were observed to be 0.119 ± 0.02 and 0.026 ± 0.006 respectively. The maximum removal of turbidity through SOABR was 85% ± 3% and cumulatively in FICCO reactor by 96% ± 0.7%. The colloidal and extremely fine particulates in wastewater are the major sources for turbidity and the removal of turbidity is a very important aspect in wastewater treatment. The faecal coliform (FC) attached to the suspended solids was removed by sedimentation. The free dispersed faecal coliform attached to colloidal particles were adsorbed onto the packing carrier matrix, and it facilitated the removal of coliform (Sehar et al., 2011; Tawfik et al., 2012). Zhao et al. (2009) reported the turbidity removal by 99% using anaerobic-anoxicoxic membrane bioreactor. The initial concentration of total coliform bacteria in domestic wastewater was found to be 29 × 10^6 ± 30 × 10^7 CFU/mL at different sampling periods (Table 2). The total coliform concentration after treated in SOABR was found to be 3 × 10^3 ± 2 × 10^4 CFU/mL and after treated in FICCO reactor it was observed to be 25 × 10^2 ± 2 × 10^4 CFU/mL. The coliform bacteria were removed by 92% ± 8.8% in SOABR and cumulatively 99% ± 1.3% in FICCO reactor. There are similar reports on the removal of pathogens, Tawfik et al. (2010) confirmed the FC removal efficiency by 98.8% using integrated UASB and MBBR system operated at an HRT of 13.3 hr. Wang et al. (2014) reported turbidity removal by 99% using AnSMBR operated for 160 days. Khan et al. (2015) reported faecal coliform removal by 80%-87% and E. faecalis removal by 80%-88% in combined application of FBR (fixed biofilm reactor) and SCF (sand column filter) systems.

2.2. Performance of COD removal by integrated SOABR and FICCO reactors

The domestic sewage with COD of 573 ± 93 mg/L was applied to the reactors at an OLR of 191 ± 31 mg/L·l-hr. The COD remained after treatment through SOABR and FICCO reactors at the start-up period were 203 ± 75 mg/L and 67 ± 42 mg/L respectively with percentage removal by 63% ± 12% in SOABR and cumulatively by 87% ± 7% in FICCO reactor. The COD remained in SOABR reactor was 140 ± 20 mg/L and in FICCO reactor it was 33 ± 5 mg/L with the removal efficiency of 75% ± 2% in SOABR and cumulatively 94% ± 1% in FICCO reactor (Fig. 2b) up to 120 days under continuous mode of operation. Zhang et al. (2017) reported the COD removal by 95% ± 3% in sewage treatment using anoxic-anoxic process and Zhao et al. (2009) reported the COD removal by 87% ± 1.6% from coke wastewater using anaerobic-anoxicoxic membrane bioreactor. Leyva-Díaz et al. (2013) reported 91% ± 2%, 90% ± 2% and 90% ± 3% of COD removal efficiency on WWTP 1 (wastewater treatment plant), WWTP 2 and WWTP 3 using combined MBBR-MBR. Thus, the present investigation confirms the integration of SOABR with FICCO reactor increased the COD removal efficiency. The plastic carrier media used for the biofilm growth provided a large surface area for the growth of microorganisms (Guo et al., 2010). The biofilm growth was mostly observed in the inner surface of the carrier media, indicating that the hydraulic rupture and mechanical abrasion were less drastic for the growth of biofilm. Hence, the incorporation of plastic carrier media significantly enhanced the growth of biomass in the SOABR (Deng et al., 2016). The combined SOABR-FICCO process showed the maximum removal of COD by 94% ± 1% with residual COD in the treated sewage was 33 ± 5 mg/L. There are reports on combination of hybrid reactors for sewage treatment, Ling et al. (2006) reported that COD was removed by about 80% through hydrolyzation film bed (HFB) and biological aerated filter (BAF) systems in sewage treatment. Chatterjee et al. (2016) reported that COD was removed by 99% in UASB – MBBR followed by rope bed biofilm reactor (RBBR) at an OLR of 2 kg COD/m³·day. Tawfik et al. (2010) reported that the UASB–MBBR system removed COD by about 80%-92% at HRT 5–13.3 hr.

2.3. Performance of integrated reactors on BOD₅ removal

The BOD₅ removal by SOABR and FICCO reactor are illustrated in Fig. 2c. The sewage fed to the reactors contained BOD₅ in the range of 197 ± 35 mg/L. The BOD₅ remained in the treated sewage was found to be 85 ± 43 and 34 ± 17 mg/L with removal efficiency of 58% ± 16% and cumulatively 83% ± 6% respectively after treatment with SOABR and FICCO reactor during start-up period. The BOD₅ remained in the sewage after treatment with SOABR and FICCO reactor was 41 ± 9 and 9 ± 0.8 mg/L respectively under continuous mode of operation for 120 days with removal efficiency of 78% ± 4% in SOABR and cumulatively 95% ± 0.6% in FICCO reactor. The removal of BOD₅ may be attributed to the growth of heterotrophic bacterial film on the plastic packing media in SOABR and NPAC in FICCO reactor. Leyva-Díaz et al. (2013) reported 99 ± 0.57, 98 ± 0.40 and 98 ± 0.44 of BOD₅ removal efficiency on three wastewater treatment plants using combined MBBR-MBR. Ling et al. (2006) reported that BOD₅ was removed from sewage by 84.4% to 90.8% using HFB–BAF system at an applied OLR of 0.338 to 0.649 kg/(BOD₅·m³·day). The SOABR–FICCO technology exhibited effective BOD₅ removal than the technologies reported by other researchers (Tawfik et al., 2012; Khan et al., 2015).

2.4. Total suspended solids removal

The concentration of TS, TDS, and TSS in untreated sewage and after treatment with SOABR and FICCO reactor is presented

---

**Table 1 – Characteristics of untreated domestic sewage.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Std. dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.32</td>
<td>6.94</td>
<td>6.65</td>
<td>0.18</td>
</tr>
<tr>
<td>ORP (mV)</td>
<td>−293.8</td>
<td>−221.4</td>
<td>−259.4</td>
<td>−19.62</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>320</td>
<td>906</td>
<td>573.82</td>
<td>93.20</td>
</tr>
<tr>
<td>BOD₅ (mg/L)</td>
<td>106</td>
<td>302</td>
<td>197.79</td>
<td>35.14</td>
</tr>
<tr>
<td>TS (mg/L)</td>
<td>590</td>
<td>1520</td>
<td>921.66</td>
<td>205.27</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>300</td>
<td>960</td>
<td>471.38</td>
<td>153.51</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>180</td>
<td>960</td>
<td>450.28</td>
<td>136.59</td>
</tr>
</tbody>
</table>

*a Oxidation reduction potential (ORP); Chemical oxygen demand (COD); Five day biochemical oxygen demand (BOD₅); Total solids (TS); Total dissolved solids (TDS); Total suspended solids (TSS).
The raw sewage was characterized by TS, 921 ± 205 mg/L; TDS, 471 ± 153 mg/L and TSS, 450 ± 136 mg/L. The TS, TDS and TSS were removed by 48.94% ± 14.04%, 24.64% ± 10.83% and 46% ± 19% (255 ± 198 mg/L) in SOABR during its start-up period. The TS, TDS and TSS removal efficiency by SOABR under continuous mode of operation up to 120 days were 54% ± 9%, 26% ± 11% and 87% ± 6% (55 ± 26 mg/L) respectively. The TDS removal in SOABR was only 26% ± 11% and the violent fluctuation in TDS removal may be attributed to daily change in the concentration of TDS in sewage collected from treatment plant and bacterial inefficiency to accumulate the mineral ions (Fig. 2e). The heterotrophic bacterial biofilm present on the carrier matrix was efficient enough to biosorb and metabolize the TSS, and thus TSS removal was 87% ± 6%. The integrated SOABR and FICCO reactor have established the maximum removal of TS, TDS and TSS during their start-up period were found to be 58% ± 12%, 37% ± 8% and 57% ± 19% (204 ± 179 mg/L) respectively. The treated sewage was characterized by TS, 260 ± 32 mg/L; TDS, 234 ± 20 mg/L and TSS, 17 ± 9 mg/L under continuous mode of operation for 120 days with the removal efficiency of 68% ± 7%, 43% ± 9% and 95% ± 4% respectively. TDS removal in FICCO reactor was 45–50%, due to
utilization of dissolved nutrients by microalgae biofilm in the reactor (Ruiz-Marin et al., 2010; Gao et al., 2015).

The conventional primary clarification process employing alum and polyelectrolyte as coagulants was reported to achieve TSS removal by 50%–65% (WEF, 2007). The SOABR technology was efficient enough to remove TSS by 95% ± 4% at HRT of 3 hr. Thus, the biofilm grown onto the plastic media may be attributed to the removal of suspended solids through physical interception or through microbiological processes (Hahn and Figueroa, 2015; Pronk et al., 2015; Chatterjee et al., 2016). Leyva-Díaz et al. (2013) reported the TSS removal efficiency was 95% ± 4%, 95% ± 4% and 94% ± 3% in WWTP 1, WWTP 2 and WWTP 3 respectively using combined MBBR-MBR. In the present investigation, the sludge collected from SOABR after continuous treatment of volume 13.3 m³ for 120 days was only 4361 g with 93% of moisture content. The sludge generated after the treatment of raw sewage stakes only 5.1% of the applied TSS to the reactor. The microbiological hydrolysis and oxidation reactions that occur in SOABR may be attributed to the retarded sludge generation. The wet sludge generation by 76,950 g may be anticipated from a primary clarifier with 90% efficiency if used for the treatment of above sewage. Hence, SOABR may be considered as an effective alternative unit operation over primary clarifier for the treatment of domestic wastewater with minimum sludge production and minimum electrical energy consumption.

**2.5. Characterization of sludge**

The sludge was collected through the sludge collection outlets from SOABR and FICCO reactor after continuous operation for 120 days and characterized for SVI. The SVI reflects the sludge settling tendency, and it can be considered as a parameter for the ability to form granular sludge for the considerable mean cell residence time in a reactor (Yu et al., 2014). The observed SVI for the sludge collected from SOABR after continuous operation for 120 days was 32 mL/g and the same for the sludge collected from FICCO reactor was 46 mL/g (Fig. 3), which is observed to be lower than the sludge collected from activated sludge process (100–150 mL/g). The lower value of SVI indicates the better settling ability of sludge (Yasui and Shibata, 1994; Chen et al., 2001; Wei et al., 2003; Fang et al., 2015). Thus, the granular sludge generated in the SOABR had an excellent settling ability and thus HRT was optimized at 3 hr and the same was maintained in further experiments. The specific gravity of selected fresh plastic packing media was 0.6076 and the same was increased to 0.9468 after 120 days operation in SOABR, owing to biofilm growth onto internal surface area of the media. Thus, the plastic media were freely floating inside the reactor without abrading one another in SOABR. The suspended solids in the sewage before and after applied to SOABR were 450.28 ± 136.59 mg/L and 55 ± 26 mg/L respectively. The collected wet sludge from the SOABR after 120 days of operation or treating 13.3 m³ of sewage was 4361 g with 93% of moisture content against the anticipated mass of sludge was 85,500 g (with 93% of moisture content). This illustrates that 94.9% of total suspended solids were removed through microbial digestion during the period of operation in SOABR. Thus, SOABR may be considered as an efficient unit operation for the treatment of wastewater with minimum sludge generation. The sludge collected from SOABR contained volatile solids by 0.662 g/g and fixed solids by 0.337 g/g. After continuous operation for 120 days the FICCO reactor generated the sludge by 4.2 g with 90% of moisture content. The poor sludge yield in FICCO reactor is due to retarded microbial multiplication rate by immobilized bacterial biomass in NPAC matrix. The sludge collected from FICCO reactor under continuous mode of operation was characterized by volatile suspended solids, 0.824 g/g and fixed solids, 0.176 g/g of dry sludge. The high fraction of VSS in the sludge may be assumed to be due to microbial mass and fixed solids may be attributed to the precipitated inorganic solids from the dissolved ions (calcium, magnesium, heavy metals, sulphate, carbonate and phosphate ions) and grit solids present in the raw sewage (Tawfik et al., 2010; Buntner et al., 2013). The results observed in the present investigation corroborates with the observation recorded by other researchers on lower sludge formation in sewage treatment (Tawfik et al., 2012; Barros et al., 2015; Pronk et al., 2015; Chatterjee et al., 2016).
Fig. 4 – Thermo gravimetric analysis (a) and differential scanning colorimetry (b) of SOABR and FICCO reactor sludge.

Fig. 5 – The cylindrical plastic packing media used in SOABR system (a) on 0th day, (b) the microbial biofilm formed on 20th day and, (c) the microbial biofilm formed after 120th day of continuous operation, (d) scanning electron microscopy of microbial biofilm at start-up period and, (e) SEM micrograph of microbial biofilm formed on 120th day of continuous operation.
2.6. TGA and DSC analyses of sludge generated from SOABR and FICCO reactor

The steady loss of mass up to 118°C observed may be attributed to the expulsion of water molecules. It is followed by a static condition up to 260°C, this may be due to the decomposition of low volatile organic compounds which has the boiling point in the range between 118 and 260°C. The sludge samples collected from both the reactors were decomposed until 260°C and thereafter certain deviations were observed due to the changes in their composition. The residue (fixed solids) left behind the two sludge samples were also different. The sludge collected from FICCO reactor contained the fixed solids by 31.22% and SOABR sludge contained the fixed solids by 32.36% indicating more of inorganic compounds were present in SOABR sludge compared with the FICCO sludge (Fig. 4a).

The dried sludge samples collected from SOABR and FICCO reactor were analysed in DSC. The thermogram showed small exothermic peak for SOABR sludge and large exothermic peak for FICCO sludge. This indicates that more mineralised sludge is generated in SOABR compared to the FICCO reactor. This reveals that the composition of the sludge samples generated in the two reactors differ widely, owing to the different microbial diversities present in the respective reactors. SOABR contains facultative bacteria and flocculent bacteria while the FICCO reactor accommodates only the aerobic microorganism. The sludge generated in SOABR contain endothermic peak at 222.5°C, this implies that the sludge contained very low carbonaceous solids and more of inorganic solids (Fig. 4b).

2.7. SEM analysis

The cylindrical plastic packing media used in SOABR (Fig. 5a) for microbial mass attached growth were collected from the reactor on 20th and 120th days of operation for characterization of the sludge (Fig. 5b–c). The SEM images of plastic media packed in SOABR were collected after 20th and 120th days of continuous operation showed the formation of microbial biofilm in the carrier matrix (Fig. 5d–e). The filamentous bacterial biofilm formed onto plastic media increased its specific gravity (0.94), and it aided to move freely in the reactor and thereby increased the treatment efficiency. The NPAC used in FICCO reactor for the immobilization of microorganism was collected and SEM images were captured as shown in Fig. 6a and b. The micrographs clearly reveal that the NPAC is porous in nature. The pores distributed in NPAC supported the growth of microorganisms to form biofilm. The NPAC collected from the FICCO reactor on the 20th day showed the presence of microbial growth on the surface of NPAC (Fig. 6c).

Fig. 6 – SEM images of nanoporous activated carbon, (a-b); the NPAC after 20th day, (c); the nanoporous activated carbon (NPAC) on 120th day of operation, (d).
The SEM image of NPAC collected from FICCO reactor on 120th day showed the microbial film in the pores of NPAC (Fig. 6d). The microbial film formed in the pores of NPAC facilitated the degradation of persistent organics in wastewater during treatment in FICCO reactor. The SEM pictures of the biofilm formed onto the plastic packing media used in the FICCO reactor are shown in Fig. 7a and b, it showed the growth of diatoms (microalgae) onto the packing carrier matrix and it helped in the removal of nutrients and thereby it showed 45%–50% of TDS removal.

2.8. Seed germination study

The seed germination study was carried out with the treated domestic wastewater derived from integrated SOABR-FICCO system, untreated sewage water and normal potable water served as control, and the results are presented in Table 3. The germination rate was found to be 83%, 85% and 90% for treated sewage, control and untreated sewage respectively. The coefficient of the velocity of germination (CVG) was found to be high in untreated sewage (0.6602) than with the treated sewage water (0.5110) and control (0.6008). The daily germination speed (DGS) were 0.084, 0.072 and 0.078 with the treated effluent, control and untreated sewage respectively. The improvement in the germination speed in treated sewage water is due to the removal of pathogens and organic matter from sewage. The observed root and shoot lengths of the plants were 4.63 cm and 2.96 cm for the plant grown with treated sewage. The root and shoot lengths of the plant grown with untreated sewage were found to be 3.75 cm and 2.5 cm respectively and the parameters for the control were found to be 4.369 cm and 2.091 cm respectively. The untreated sewage exhibited the retardation in root and shoot growth due to the presence of high amount of complex organic/inorganic compounds. The mean daily germination (MDG) index for the seeds with treated sewage water, untreated sewage water and control were calculated to be 11.8, 12.8 and 13.8 respectively. The vigour index for seed germination was found to be 536.18, 629.97 and 562.5 for the seeds raised with control water, untreated sewage and treated water respectively. This corroborates with the findings recorded by the other researchers on seed germination for the diluted untreated sewage water (Dash, 2012; Singh and Srivastava, 2012; Sinha and Paul, 2013; Manisha and Angoorbala, 2013; Hu et al., 2016).

2.9. Economics of the SOABR-FICCO process

The total time required for the treatment of sewage through integrated SOABR-FICCO system is only 9 hr. The SOABR reactor has very high efficiency (95%) in removing suspended solids without application of coagulants as against observed in conventional treatment technology. Hence, there is a huge scope to have following features; Low investment cost (the technology requires very low foot print area because it requires only two unit operations and less electro mechanical equipment); low maintenance cost (the technology does not require chemicals and other consumables); low sludge production (the technology produces only 5.1% of the TSS applied load and thus sludge disposal cost is very less); less electrical energy consumption (the technology requires very less electro mechanical equipment); less operational cost (considering the saving on electrical energy, chemical conservation, limited

### Table 3 – Seed germination index of treated and untreated sewage.

<table>
<thead>
<tr>
<th></th>
<th>Germination rate</th>
<th>CVG</th>
<th>MDG</th>
<th>DGS</th>
<th>Shoot length (cm)</th>
<th>Root length (cm)</th>
<th>Vigour index (SLVI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>85%</td>
<td>0.6008</td>
<td>13.8</td>
<td>0.072</td>
<td>4.369</td>
<td>2.091</td>
<td>536.18</td>
</tr>
<tr>
<td>Untreated sewage</td>
<td>90%</td>
<td>0.6602</td>
<td>12.8</td>
<td>0.072</td>
<td>3.75</td>
<td>2.5</td>
<td>629.97</td>
</tr>
<tr>
<td>Treated effluent</td>
<td>83%</td>
<td>0.5110</td>
<td>11.8</td>
<td>0.084</td>
<td>4.63</td>
<td>2.96</td>
<td>562.5</td>
</tr>
</tbody>
</table>

CVG: coefficient of the velocity of germination; MDG: mean daily germination; DGS: daily germination speed; SLVI: seedling’s length vigor index.
man power requirement in SOABR-FICCO system, the running cost for the treatment of unit volume of sewage is expected to be 0.12 USD/m³).

The integrated SOABR and FICCO reactor showed high economic feasibility with less investment cost than MBR technology (Lin et al., 2012).

3. Conclusion

The integrated SOABR and FICCO reactor were employed for the treatment of domestic wastewater in the present investigation under continuous mode of operation. The integrated SOABR-FICCO reactors removed COD, 94% ± 1%; BOD₅, 95% ± 0.6%; TSS, 95% ± 4% and total coliform, 99% ± 1.3% from domestic sewage. The sludge produced in SOABR and FICCO reactor system was found to be less than in any other systems reported by the other researchers. The vigour index 562.5 for the seed germination confirmed the removal of organic and suspended impurities by SOABR-FICCO reactor. Thus, the proposed integrated SOABR-FICCO system may be considered as a novel method for the treatment of domestic waste water with minimum sludge production.

Acknowledgment

The author M. Mahesh is thankful to Council of Scientific and Industrial Research (CSIR) – Central Leather Research Institute (CLRI), India, for awarding Senior Research Fellowship (grant number 31/6(429)/2017-EMR-I). The authors are grateful to Director, CSIR–CLRI, India, for granting permission to carry out this research work. The authors are also thankful to CSIR for providing the financial support under the project STRAIT (CSC0201).

References


Qiu, G., Song, Y., Zeng, P., Duan, L., Xiao, S., 2013. Combination of upflow anaerobic sludge blanket (UASB) and membrane bioreactor (MBR) for berberine reduction from wastewater and the effects of berberine on bacterial community dynamics. J. Hazard. Mater. 246-247, 34–43.


