

Textile effluent treatment by fungi MBR with sludge bed /GAC adsorption: Long-term performance of compact hollow-fiber module and overall treatment

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Abstract The performance of an innovative fungi-MBR containing a sludge bed beneath the main aerobic zone was observed as the feed (artificial textile wastewater) to the reactor was split to its top (aerobic zone) and bottom (sludge bed) in different ratios. The average stable MLSS_{aerobic} concentrations in case of feeding from top, bottom or simultaneously from top (60%)-bottom (40%) were 25, 4 and 11 g/L, respectively. Feeding mode and MLSS concentration played a significant role in color and TOC removal. The respective average color and TOC removals in case of feeding from top, bottom or simultaneously from top (60%)-bottom (40%) were as follows: Color (93.2%, 57.5%, 91.3%), TOC (97%, 94%, 97%). Depending on the type of dye, the biomass at the settling zone offered considerable sorption, thereby aiding in overall decoloration (99.7%). When required, GAC post treatment furnished an excellent means to complement MBR treatment. In addition to accomplishment of excellent color and TOC removal, membrane fouling was successfully precluded by utilizing newly developed compact spacer-filled hollow-fiber modules. Periodic *in situ* chemical backwashing with a small dose (500 mg Cl/L, 100 ml/m², twice/week) and intermittent surface-cleaning with a specially designed aeration device (1 min/30 min @ 1 L air/min) enabled stable operation for an observation period of around six months under the selected average flux (1.27x10⁻⁷ m/s) and MLSS concentration (~10 g/L).

Keywords Fungi MBR; GAC adsorption; hollow-fiber module; textile wastewater

INTRODUCTION

Textile wastewater is a complex and highly variable mixture of many polluting substances, including dye, which induce persistent color coupled with organic load leading to disruption of the total ecological balance of the receiving water stream (Robinson *et al.*, 2001). Several physicochemical decolorization techniques have been reported (e.g. adsorption, membrane separation, advanced oxidation process), none, however, has appeared as a panacea due to high cost, low efficiency and inapplicability to a wide variety of dyes. Biodegradation is an environmentally friendly and cost competitive alternative; but the conventional aerobic treatments have been proved ineffective while highly toxic aromatic amines can be formed by reductive fission under anaerobic conditions. Accordingly researchers have put forward diverse innovative approaches, which, however, await practical implementation (Hai *et al.*, 2007). For instance, although literature is replete with reports demonstrating the excellent capacity of white-rot fungi to degrade recalcitrant dye effluent, so far, their application in large-scale waste treatment has been impeded by the lack of bioreactor systems that can sustain steady production of high levels of enzymes for a prolonged period together with a controlled growth of fungi.

We previously developed a submerged membrane bioreactor (MBR) implementing a white-rot fungus for effective treatment of textile dye wastewater (Hai *et al.*, 2006a). In addition to

accomplishment of excellent color and total organic carbon (TOC) removal, the membrane fouling in that system was successfully mitigated by adopting some unique techniques. However, the inherent vulnerability of the commercial hollow-fiber modules to inter-fibril deposition of sludge indicated necessity of development of an appropriate module. Conversely, in view of the intensive sludge-growth owing to the typical high dose of starch (carbon source) as required for maintaining the viability of the fungi during that study, formulation of an improved reactor-design was deemed imperative.

This study investigated the performance of an innovative ‘fungi MBR’ with a settling zone beneath the main aerobic zone bearing the membrane modules. Newly developed compact hollow fiber modules with spacer were utilized. A granular activated carbon (GAC) column was introduced for the post treatment of the MBR-permeate. This communication reports the effect of such reactor design and the overall treatment performance of the explored scheme as well as the long-term performance of the hollow-fiber module.

METHODS

This study involved experiments employing an artificial textile wastewater in a specially designed bioreactor within which newly developed hollow-fiber modules containing spacer were submerged. The MBR was initially inoculated with pure culture of fungi; however, it was operated, other than controlling pH (4.5 ± 0.2) and temperature ($29\pm 1^\circ\text{C}$), under non-sterile conditions.

Microorganism and synthetic wastewater

The white-rot fungi *C. versicolor* NBRC 9791 obtained from the NITE Biological Resource Center (NBRC), Japan was used for this study. A nutrient-sufficient synthetic wastewater (TOC= 2g/L) containing dye (either of the two azo dyes: Acid Orange II, Poly S119; 100 mg/L) and starch (4.5 g/L)—two common components in real textile wastewater—along with other nutrients, was utilized. Details regarding the media have been documented elsewhere (Hai *et al.*, 2006a).

Design and operating conditions of the bioreactor

A laboratory scale bioreactor, made of PVC, with a total working volume of 22.25 L was used in this study. An air-diffuser (air-flow=5 L/min.) was placed at a distance of 25 cm from the reactor-bottom, leaving a volume of 9.98 L beneath it, thereby allowing formation of a settling zone (Figure1). A certain percentage of the total feed was introduced from a port located at the bottom of the reactor, while the rest was simultaneously added from the top. The adopted reactor-design and split-mode feeding strategy were aimed at two probable accomplishments—minimization of excess sludge-growth and maintenance of less MLSS concentration in contact with the membrane at the upper zone (henceforth referred to as ‘MLSS_{aerobic}’), and stabilization of the dye removal against possible fluctuation of biological activity making use of the sorption of dye onto the settled biomass.

Membrane modules

Spacer-filled bundles of micro-porous (0.4 μm) polyethylene hollow-fibers obtained from Mitsubishi Rayon, Japan were utilized in this study. The aim of introducing spacer was to avoid merging of fibers by reducing intrusion of sludge into the module as much as possible. The utilized modules possessed the same dimensions (Diameter=4.5 cm, Height= 22 cm), but different surface areas ranging from 0.93 to 1.07 m² depending on the type of spacer. Spacers of different rigidity and pore-size, imparting different degrees of compactness to the modules, were explored. Preliminary explorations of modules containing either a rigid (1 mm thickness and 7mm x 7mm openings) or a thin spacer (1 mm x 1mm openings) were followed by that of a ‘hybrid module’ which was obtained by winding the rigid spacer around the module having thin spacer (Figure 2).

The membranes were operated under an average flux of 1.27×10^{-7} m/s with 5 min. on/off mode. Pulsed backwash with permeate (3s/ 10 min. @ 1.67 ml/s) was always applied to the modules, while chemical cleaning was performed with NaOCl solution containing 500-3000 mg Cl /L (100 ml per m² membrane surface; twice/week) depending on the specific trial.

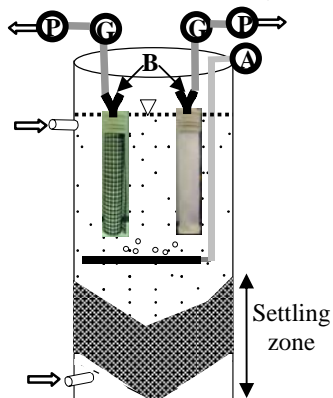


Figure 1 Schematic of laboratory setup (A: Air pump, B: Backwash, G: Vacuum gauge, P: Pump)

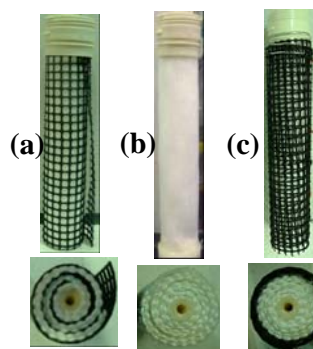


Figure 2 Side and bottom views of modified modules (a) Rigid spacer, (b) Thin spacer, (c) Rigid mesh wound around 'module b' (hybrid module)

Granular activated carbon (GAC) column

A 6.5 cm diameter PVC column containing 1.33 L of GAC F400-OS (Calgon Mitsubishi Chemical Corporation, Japan) was utilized in this study. The grade of GAC used here is one of the most widely used ones in the water treatment industry and has been previously reported as a good adsorbent for dye wastewater treatment (Walker *et al.*, 2001). The column was operated in up-flow mode under constant volumetric and linear flow rates of 20 ml/min and 0.603 cm/min, respectively, thereby resulting in an empty bed contact time (EBCT) of 66.37 min.

Analytical methods

TOC was measured with a Total Organic Carbon analyzer (TOC-V, Shimadzu). The absorbance of the sample at the peak wavelengths (481 and 472 nm for Orange II and Poly S119, respectively) of the dyes used was measured using a spectrophotometer (U-2010, Hitachi). The concentration of dyestuff was calculated from a 'absorbance vs. concentration' curve and concentration values were used for calculations of decolorization efficiency. Mixed liquor suspended solids (MLSS) concentration was measured according to the standard methods (APHA/AWWA/WEF, 1998). Transmembrane pressure (TMP), as an indicator of membrane fouling, was continuously monitored using a vacuum pressure gauge (GC 61, JUST). Also direct assessment of membrane fouling was performed through visual observation of the fouled membrane by lifting it up above the water level periodically and occasionally performing membrane-autopsy.

RESULTS AND DISCUSSION

Effect of feeding mode and reactor design on MBR performance

A frequently reported problem associated with long-term operation of reactor containing white-rot fungi is the intensive sludge-growth due to the high dose of carbon source as required for maintaining the viability of the fungi (Zhang *et al.*, 1999; Hai *et al.*, 2006a,b). In this study a reactor with a sludge bed and a split-mode feeding strategy were explored for minimization of excess sludge-growth and maintenance of lesser MLSS concentration in direct contact with membrane to improve ease of fouling mitigation.

Table 1.Decoloration of Acid Orange II^a dye in the MBR

Feeding mode, %		Avg. MLSS, g/L	Avg. removal, %		
From top	From bottom		pH	Color	TOC
0	100	4	7 4.5	12.6 57.5	94 54.1 ^b -94 ^c
100	0	25	4.5	93.2	97
60	40	11	4.5	91.3	97

^aBiosorption[mg dye/g dry biomass wt]=0.81^{b,c}With and without chemical wash of membrane**Table 2.**Decoloration of Poly S119^a dye in the MBR

Feeding mode, %		Avg. MLSS _{aerobic} , g/L	Avg. removal, %	
From top	From bottom		Color	TOC
60	40	11	96.8 ^b - 99.7 ^c	97

^aBiosorption[mg dye/g dry biomass wt]=10.4 l^bComplete media including dye split in 60-40 ratio,^cMedia excluding dye split in 60-40 ratio while all the dye fed from bottom

MLSS concentration. In accordance with our expectation, the adopted reactor design and feeding mode proved to be an efficient means to control the MLSS_{aerobic} concentration. The average stable MLSS_{aerobic} concentrations varied from 4 to 25 g/L depending on the feeding mode (Table1). Introduction of whole of the media from the top of the reactor led to massive increase in MLSS_{aerobic} (25 g/L), while feeding only from the bottom caused gradual accumulation of poorly soluble starch (carbon source) at the settling zone and a far lower MLSS_{aerobic} (4 g/L). Splitting of feed to the top and the bottom in a 60%-40% ratio along with a simple arrangement of recirculation of settled starch enabled maintenance of an average MLSS_{aerobic} of 11 g/L.

Color and TOC removal. Feeding mode and MLSS concentration played a significant role in color and TOC removal (Table1). For 60%-40% (top-bottom) split of feed (MLSS_{aerobic} =11 g/L), the color and TOC removal ranged around 91.3% and 97%, respectively. A slight improvement in decoloration rate (93.2%) was observed for feeding only from the top (MLSS_{aerobic} =25 g/L). The extent of decoloration in case of feeding only from bottom (MLSS_{aerobic} =4 g/L) varied from 57.5% under pH=4.5 to 12.6% under pH=7. The average TOC removal for this case in presence and absence of chemical cleaning of membrane stood at 54.1% and 94% (both at pH=4.5), respectively. The maximum decoloration achieved in this case (57.5%) was well below those achieved with other feeding strategies, indicating requirement of appropriate MLSS_{aerobic} for stable decoloration. On the other hand, the marked dependence of decoloration on pH or hindered TOC removal in presence of chemical cleaning of membrane was of special interest. Dose-specific adverse effect of membrane-cleaning chemical (NaOCl) on biological activity has been previously reported (Lim *et al.*, 2005). However, the observed phenomena in our study may be attributed to the pronounced competition between fungi and bacteria under the limiting nutritional condition that existed in the aerobic zone when all the feed was introduced through the sludge-bed. In this case, with a noteworthy portion of starch accumulated in the settling zone, nutrient supplied to the upper aerobic zone was insufficient, and, hence, depending on the pH, fungi or bacteria attained complete dominance. The reactor was originally planned to be operated under acidic pH favorable to fungi with the expectation that fungi—the main decolorizing agent—would attain slight dominance, but bacteria—the main TOC remover—would still remain functioning. However, nutrient limitation may have caused disruption of that subtle balance. Accordingly, in case of insufficient nutrient supply, under acidic pH, the TOC removal performance of bacteria was affected by chemical cleaning of membrane, while decoloration by fungi was affected under neutral pH favorable to bacteria. In this context it is worth-mentioning that a feeding strategy involving split of the feed to the top and the bottom of the reactor in a 60%-40% ratio may be utilized from the points of view of color and TOC removal as well as maintenance of moderate MLSS_{aerobic}.

Effect of dye type on MBR performance

Depending on the type of dye and level of enzymatic activity, sorption on fungal mass may play a significant role in total decoloration (Fu *et al.*, 2001; Hai *et al.*, 2006b). One aim of introducing the

reactor design with sludge bed and feeding a certain portion of the wastewater through this bed was to stabilize dye removal performance against possible fluctuation of biological activity making use of the sorption property of dye onto the settled biomass. However, the dye (Acid Orange II) utilized for the first part of this study showed limited sorption on biomass (0.81 mg dye/g dry biomass) and, hence, the effect of such strategy could not be clearly assessed in that case. Accordingly, the reactor was next fed with a wastewater containing another azo dye Poly S119 exhibiting considerable biosorption (10.41 mg dye/gm dry biomass). An average decoloration of 96.8% was achieved when the feed was split in 60%-40% ratio, top-bottom (Table 2). It is worth reiterating here that under the same feeding strategy a decoloration of 91.3% was achieved for the dye with lower biosorption. Since the biodegradability of the dyes was not significantly different (data not shown), our observation indicated that biosorption on sludge bed enhanced total decoloration. A further improved decoloration of 99.7% was observed when the wastewater containing all other constituents except dye was split in 60%-40% ratio, while all the dye was fed from the bottom. This further substantiated the role of biosorption on sludge bed. Since different streams of wastewater in a textile mill originate from different plants, namely, scouring, desizing, dyeing, rinsing, printing etc., such a feeding strategy may be adopted in practical case too. Excellent decoloration in case of this dye was accompanied by a marked reduction in UV absorbance (Figure3).

The advantage of the proposed reactor design has been convincingly demonstrated in case of a dye exhibiting high biosorption. However, the enzymatic activity within reactor was much less than that observed in pure culture batch test (data not shown), and, the fact that removal of a dye with lower biosorption was somewhat lower indicates that there is a scope for further improvement in terms of treatment of a wide variety of dyes possessing different structures and biosorption properties. Our ongoing investigation has detected some critical parameters, namely, bacterial disruption of secreted enzyme and/ or inactivation of fungal enzymatic activity, loss of enzyme with permeate etc. and our preliminary results indicate that maintenance of certain morphology of fungi within the reactor may facilitate stable enzymatic activity and appropriate decoloration.

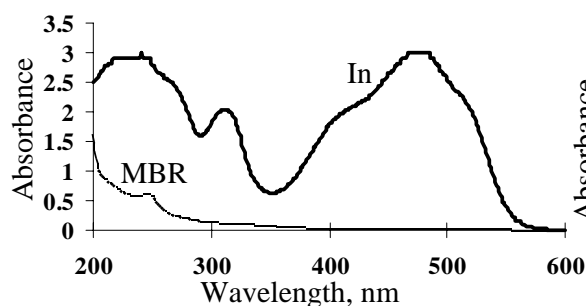


Figure 3 Typical observed change in UV-VIS spectra following MBR treatment of Poly S119 dye (high biosorption)

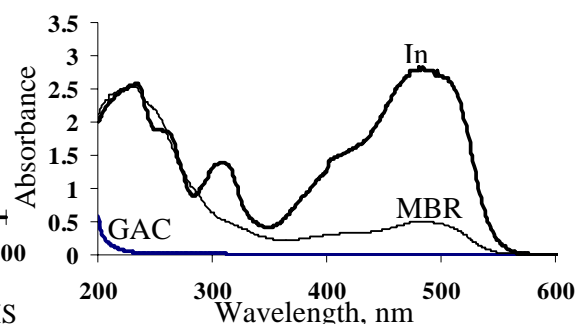


Figure 4 Typical observed change in UV-VIS spectra following MBR-GAC treatment of Orange II dye (low biosorption)

Post treatment by GAC adsorption

The excellent adsorption properties of carbon-based supports have been extensively utilized for decolorization of industrial dye wastewater (Hai et al., 2007). GAC adsorption in particular has been explored both as the sole (Walker et al., 2001) or as a post treatment (Rozzi et al., 1999) option. Biological treatment systems may be subject to occasional malfunctions leading to inappropriate decoloration. Under such a circumstance a GAC post treatment unit may be useful as an emergency unit to be utilized until the performance of the biological unit is recovered.

In this study, the removal of Acid Orange II dye from wastewater by the MBR was incomplete and, hence, GAC post treatment was introduced. The performance of the GAC column as a post

treatment unit was observed while it was continuously fed with MBR-permeate bearing varying degree of color arising due to varying MBR-performance in response to different feeding strategies. Irrespective of the influent color, the effluent from the GAC column exhibited almost complete decoloration along with a marked diminution of absorbance in the UV range (Figure 4). The GAC column was next operated as a post treatment unit for a period of around 6 months during which the MBR was fed in a 60%-40% (top-bottom) split mode. In comparison to the decoloration in the range of 90.4%-92.2% as achieved by the MBR during the period, decoloration following the GAC treatment varied from almost 100% at the beginning to 99.6% after 6 months (Figure 5).

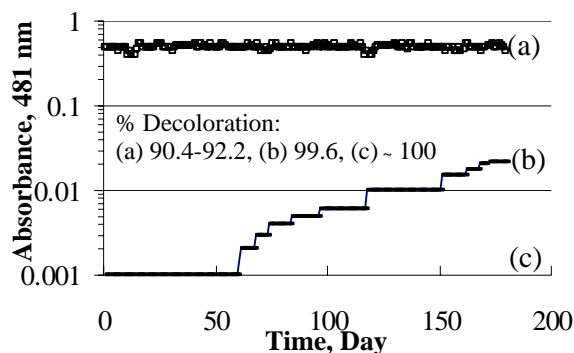


Figure 5 Long-term performance of MBR (a)-GAC (b,c) treatment sequence for Orange II dye.

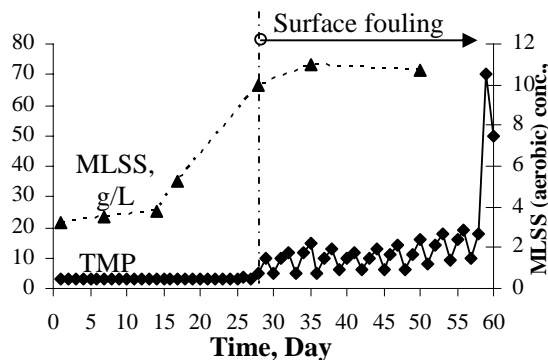


Figure 6 TMP variation during continuous operation of hybrid module under increasing $MLSS_{aerobic}$ [Chemical cleaning: 3000 mg Cl/L, 100 ml/m², twice/week]

Performance of compact hollow-fiber module with spacer

Under a $MLSS$ concentration of 5 g/L, while the usual hollow-fiber bundle exhibited fatal cake-layer fouling within a day or so, the modules with spacer sustained stable performance for a month without any chemical cleaning (data not shown). With such preliminary confirmation of the effectiveness of spacer in avoiding intrusion of sludge into hollow-fiber bundles, further investigations were conducted to assess the effect of type and arrangement of spacer, ways to mitigate surface fouling caused by sludge which, after being rejected by the module, accumulated on it, and, finally, the long-term performance of the developed module.

Effect of spacer type. Previous studies have reported on optimum fiber packing-density under different operating conditions (Sridang *et al.*, 2005; Yeo *et al.*, 2005). In this study, the fiber packing density of the modules varied in the range of 53% to 61.5% (Table 3). However, the overall compactness of the modules, which was governed by the type and arrangement of the spacers, played the critical role in avoidance of sludge intrusion and retrieval (cleaning) of the original state. The module with rigid spacer was very effective in minimizing intrusion of sludge, but it was too compact to allow complete wash-out of the small amount of sludge that eventually found its way to the core of the module (Table 3). The module with thin spacer, on the other hand, was flexible enough to allow complete washing; however, it was vulnerable to massive intrusion of sludge under higher $MLSS$ concentration (~10 g/L). Among the explored modules, a hybrid module obtained by winding the rigid spacer on the surface of a module originally containing a thin spacer exhibited the appropriate compactness so as to minimize intrusion of sludge under high $MLSS$ concentration, while simultaneously allowing periodic wash-out of the small amount of sludge trapped within it (Figure 6).

Surface fouling mitigation. The specific arrangement of spacer of the hybrid module efficiently prevented sludge intrusion within the module; however, the rejected sludge accumulated on the module-surface, and it was not appropriately scoured-off by the applied aeration in presence of high $MLSS$ concentration. Prolonged operation under such condition led to a very high TMP of 70 kPa

(Figure 6). A special aeration device was designed to appropriately clean the membrane-surface, while making an effective utilization of air. Five steel pipes (1 mm dia.) were attached on the surface of the hybrid module. The bottom ends of these pipes were bent in the form of hook and were inserted into the space in between the black-colored rigid spacer on the surface and the original module with the white-colored thin (soft) spacer (Figure 7). Air introduced from the top ends of those pipes hence effectively cleaned the membrane-surface.

Table 3. Specifications and performance of the modules utilized

Module type	Characteristics ^a		Performance
	Surface area, m ²	Fiber packing density ^b , %	
Usual	0.97	56	Fatal fouling within few days
Rigid spacer	0.93	53	Very effective in minimizing intrusion of sludge, however, too compact to allow wash-out of trapped sludge
Thin spacer	1.07	61.5	Flexible enough to allow wash-out, however, massive sludge intrusion under higher MLSS conc. (~10 g/L)
Hybrid	1.07	61.5	Stable performance under high MLSS concentration

^a Hydrophilically treated polyethylene fibers having a pore-size, outer diameter and effective length of 0.4 μm, 540 μm and 208mm, respectively, were utilized in all the modules.

^b Overall compactness of the modules, governed by the type and arrangement of the spacers, varied in the following order: rigid>hybrid>thin>usual

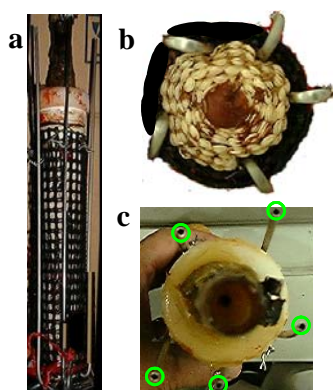


Figure 7 Surface aerator attached on hybrid module. a: side view, b: bottom view, c: top view (air inlets encircled)

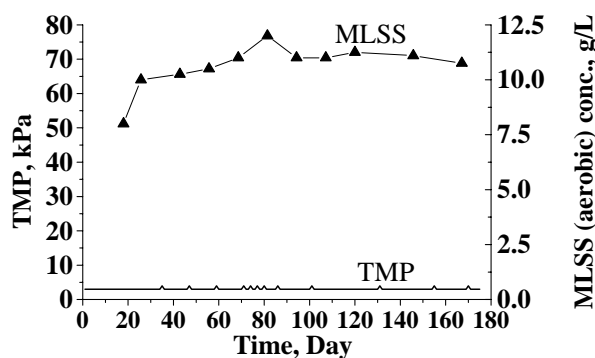


Figure 8 Long-term performance of hybrid module under cleaning (500 mg Cl/L, 100 ml/m², twice/week) and surface aeration (1 min/30 min @ 1 L air/min)

Long-term performance. Intermittent aeration (1min./30min.@ 2.5L/min.) using the above-mentioned device along with periodic chemical cleaning (3000 mg Cl/L, 100 ml/m², twice/week) allowed stable operation. No increase in TMP was observed for a prolonged period of 2 months during which the MLSS_{aerobic} concentration was varied in between 7.5-25 g/L by manipulating feeding mode, even though the chemical-cleaning dose and aeration intensity were gradually reduced to 500 mg Cl/L and 1 L/min., respectively (data not shown). Following this trial, the module was in operation for around 6 months (till the end of this experiment), under a MLSS_{aerobic} of around 10 g/L while chemical cleaning and surface-aeration were applied with small doses of 500 mg Cl/L (100 ml/m², twice/week) and 1min./30min.@ 1 L/min., respectively (Figure 8).

CONCLUSIONS

The specific conclusions drawn from this study are listed henceforth:

1. The reactor design with a sludge bed and the split-mode feeding strategy proved to be an efficient means to control the MLSS_{aerobic} concentration. The average stable MLSS_{aerobic} concentrations in case of

feeding from top, bottom or simultaneously from top (60%)-bottom (40%) were 25, 4 and 11 g/L, respectively.

2. Feeding mode and MLSS concentration played a significant role in color and TOC removal. The respective average color and TOC removals in case of feeding from top, bottom or simultaneously from top (60%)-bottom (40%) were as follows: Color (93.2%, 57.5%, 91.3%), TOC (97%, 94%, 97%). In case of feeding from bottom, marked dependence of decoloration on pH and hindered TOC removal in presence of chemical cleaning of membrane were observed.

3. Depending on the type of dye, the biomass at the settling zone offered considerable sorption while the wastewater passed through this zone, thereby aiding in overall decoloration. The MBR in this case achieved an excellent 99.7% decoloration.

4. The removal by the MBR of a dye showing negligible sorption on biomass was incomplete. In such a case, GAC post treatment furnished an excellent means to complement MBR treatment.

5. Excellent fouling prevention capacity of spacer filled hollow-fiber modules was demonstrated. Periodic *in situ* chemical backwashing with a small dose (500 mg Cl/L, 100 ml/m², twice/week) and intermittent surface-cleaning with a specially designed aeration device (1 min/30 min @ 1 L air/min) enabled stable operation for a prolonged period under the selected average flux (1.27x10⁻⁷ m/s) and MLSS concentration (~10 g/L).

Acknowledgments

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REFERENCES

- Fu, Y. and Viraraghavan, T. (2001). Fungal decolorization of dye wastewaters: a review. *Bioresour. Technol.* **79**, 251-262.
- Hai, F.I., Yamamoto, K. and Fukushi, K. (2007). Hybrid treatment systems for dye wastewater. *Crit. Reviews. Env. Sci. Technol.* **37(4)**, 315-377.
- Hai, F.I., Yamamoto, K. and Fukushi, K. (2006a). Development of a submerged membrane fungi reactor for textile wastewater treatment. *Desalination* **192**, 315-322.
- Hai, F.I., Yamamoto, K. and Fukushi, K. (2006b). Membrane-coupled fungi reactor—an innovative approach to bioremediation of hazardous dye wastewater. *Env. Sciences* **13(6)**, 317-325.
- Lim, B.-R., Ahn, K.-H., Song, K.-G. and Cho, J.W. (2005). Microbial community in biofilm on membrane surface of submerged MBR: effect of in-line cleaning chemical agent. *Water Sci. & Technol.* **51(6-7)**, 201-207.
- Robinson, T., McMullan, G., Marchant, R. and Nigam, P. (2001). Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative. *Bioresour. Technol.* **77**, 247-255.
- Rozzi, A., Malpei, F., Bonomo, L. and Bianchi, R. (1999). Textile wastewater reuse in northern Italy (COMO). *Water Sci. & Technol.* **39(5)**, 121-128.
- Standard Methods for the Examination of Water and Wastewater* (1998). 20th edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.
- Sridang, P.C., Heran, M. and Grasmick, A. (2005). Influence of module configuration and hydrodynamics in water clarification by immersed membrane systems. *Water Sci. & Technol.* **51(6-7)**, 135-142.
- Walker, G.M. and Weatherley, L.R. (2001). COD removal from textile industry effluent: pilot plant studies. *Chem. Engg. Journal* **84**, 125-131.
- Yeo, A. and Fane, A.G. (2005). Performance of individual fibers in a submerged hollow fiber bundle. *Water Sci. & Technol.* **51** (6-7), 165-172.
- Zhang, F.M., Knapp, J.S. and Tapley, K. (1999). Development of bioreactor system for decolorization of Orange II using white rot fungus. *Enzyme Microb. Technol.* **24**, 48-53.