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Fouling resistant compact hollow-fiber module with spacer for submerged membrane bioreactor treating high strength industrial wastewater

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Abstract

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Abstract

Long-term investigations carried out in a submerged membrane fungi reactor treating textile wastewater revealed the excellent fouling prevention capacity of spacer-filled hollow-fiber modules. The type and arrangement of the spacers governed the overall rigidity of the modules and played the critical role in avoidance of sludge intrusion and retrieval (cleaning) of the original state. A hybrid module (fiber packing density =61.5 %, surface area=1.07 m^2) obtained by winding a rigid spacer (thickness=1 mm, opening=7 mm x 7 mm) on the surface of a module originally containing a flexible thin spacer (opening=1 mm x 1 mm) exhibited the optimum rigidity so as to minimize intrusion of sludge while simultaneously allowing wash-out of the small amount of sludge trapped within it. Periodic *in situ* chemical backwashing with a small dose (500 mg Cl L^{-1}, 100 ml m^{-2}, twice/week) and intermittent surface-cleaning with a specially designed aeration device (aeration intensity=1 L min^{-1}, duration=1 min per 30 min) enabled stable operation for a prolonged period under the selected average flux ($7.64x10^{-6}$ m^3 m^{-2} s^{-1}) and Mixed liquor suspended solids (MLSS) concentrations (up to 25 g L^{-1}). Under the similar conditions, fourfold reduction in total consumptions of both chemical and air was possible when the developed module was placed within a coarse-pore (50-200μm) pre-filtration cage. A reactor-design with a settling zone and a feeding mode comprising split of the influent through the settling zone and from the top may be utilized to maintain an optimum MLSS concentration in direct contact with the membrane, thereby further improving the ease of fouling mitigation.

Keywords: Fouling; Hollow-fiber module; Industrial effluent, Spacer, Submerged MBR; White-rot fungi

1. Introduction

Submerged membrane bioreactor (MBR), since its introduction in the late 1980s as a cost-effective alternative to the side-stream MBR, has been successfully used for treatment of different kinds of wastewater [1]. However, membrane fouling and its consequences in terms of plant maintenance and operating costs impede the widespread use of the submerged MBR technology [2]. Usually vertical flat sheet or vertically/horizontally mounted hollow-fiber membranes are used in submerged MBRs. Each of the two types of membranes has specific

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footprint and air-scouring and chemical cleaning requirement, which may favor one process over another for a given application [3,4]. Nevertheless, hollow fiber modules are generally cheaper to manufacture, provide high specific membrane area and can tolerate vigorous backwashing [5]. For low flux operation, hollow fibers are attractive due to their high packing density. A higher fiber packing density would increase productivity; however, increasing the packing density may lead to severe interstitial blockage due to the impeded propagation of air-bubbles towards the core, limiting their effect on fouling limitation [6-8]. Attempt of chemical backwashing of the massive deposition of sludge in between fibers within a densely packed module may be less effective [9]. Hence, the challenge for system designers is to achieve uniform air-bubble effect throughout the population of fibers in a compact bundle to limit fouling so that periodic chemical cleaning can completely retrieve the initial state of the membrane.

In order to utilize high packing density without encountering severe fouling, a new approach to hollow-fiber module design was explored in this study. Spacer was introduced within usual hollow-fiber bundles with the aim of minimizing the intrusion of sludge into the module. The little amount of intruded sludge may then be backwashed through the bottom end while the sludge deposited on the surface may be effectively cleaned by air-scouring. It was expected that, in this way, efficient utilization of cleaning solution and air for backwashing and surface-cleaning, respectively, may be possible.

This study reports the superior fouling-avoidance capacity of spacer-filled compact hollow-fiber module over that of usual module under severe operating conditions induced by high strength industrial wastewater. The effect of type and arrangement of spacer, mixed liquor suspended solids concentration (MLSS), mode of air-scouring as well as dose and frequency of chemical cleaning were assessed. A reactor design to maintain appropriate MLSS concentration under high loading, thereby facilitating membrane-fouling control, was also explored. Finally, the effect of utilization of a pre-filtration device in conjunction with the developed module was discussed. Spacer-filled spiral-wound module has a long history of successful application in different sectors of water and wastewater treatment [10]. On the other hand, previous studies have focused on different operational considerations and design aspects of submerged hollow fiber membrane modules [11,12]. However, our study is the first instance where spacer has been incorporated within compact hollow-fiber module with the specific aim of fouling mitigation in case of wastewater applications.

2. Experimental

This study involved experiments employing a synthetic textile wastewater in a specially designed lab-scale 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±1°C), under non-sterile conditions. The inherent limitations of conventional biological decoloration processes led to selection of the fungi MBR [13]. Although the focal point of this study was assessment of the fouling prevention capacity of the newly developed module, simultaneous monitoring of the treatment performance of the MBR was also conducted to detect any probable effect of the adopted fouling mitigation strategies on the biological activity.

2.1 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

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containing dye (either of two azo dyes: Poly S119, Acid Orange II; 100 mg L^{-1}) and starch (4.5 g L^{-1})—two common components in real textile wastewater—along with other nutrients, was utilized. The other components of the synthetic wastewater were as follows: 0.4 g L^{-1} urea, 2 g L^{-1} KH_2PO_4, 0.099 g $L^{-1}$$CaCl_2$, 1.025 g L^{-1} $MgSO_4.7H_2O$, 0.001 g L^{-1} thiamine, 1 ml L^{-1} trace elements. The TOC of the medium was around 2000 mg L^{-1} (dye TOC≈ 50mg L^{-1}). Stock trace elements solution was prepared by dissolving 0.125 g $CuSO_4.5H_2O$, 0.05 g H_2MoO_4, 0.061 g $MnSO_4.5H_2O$, 0.043 g $ZnSO_4.7H_2O$, 0.082 g $Fe_2(SO_4)_3.14H_2O$ in 1 L of milli-Q water.

2.2 Design and operating conditions of membrane modules

Bundles of micro-porous (0.4µm) hydrophilicaly treated polyethylene hollow-fibers obtained from Mitsubishi Rayon, Japan were utilized in this study. The modules possessed same dimensions (Diameter=4.5 cm, Height= 22 cm), but different surface areas ranging from 0.93 to 1.07 m^2 depending on the type of spacer. It was anticipated that the extent of avoidance of inter-fibral intrusion of sludge may depend on the degree of overall rigidity of the module. This led to preliminary exploration of two types of spacers (**Fig.1a,b**), namely, a rigid spacer with 1 mm thickness and 7mm x 7mm openings, and a thin (flexible) one with 1 mm^2 openings (henceforth referred to as ‘rigid’ and ‘thin’ spacer, respectively). A ‘hybrid module (**Fig. 1c**)’ was also obtained by winding the rigid spacer around the module having thin spacer. **Table 1** details the specifications of the modules. The membranes were operated under an average flux of $7.64x10^{-6}$ m^3 m^{-2} s^{-1} with 5 min on/off mode in all the trials except one in which the hybrid module, placed within a pre-filtration arrangement, was operated under a flux of $1.53x10^{-5}$ m^3 m^{-2} s^{-1}. Pulsed backwash with permeate (flowrate=1.67 ml s^{-1}, duration=3 s per 10 min) was always applied to the modules, while chemical cleaning, when

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applied, was performed with NaOCl solution containing 250-3000 mg Cl L^{-1} (100 ml m^{-2} membrane surface; once or twice in a week) depending on the specific trial. After using for a certain trial, the used membrane was cleaned chemically with NaOCl solution and reused for further experiments following confirmation of retrieval of the initial flux, or replaced by a new membrane.

2.3 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^{-1}) 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 (**Fig.2**). 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 special reactor-design and split-mode feeding strategy were adopted with two expectations: i) 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, ii) stabilization of the dye removal against possible fluctuation of biological activity making use of the sorption [14] of dye onto the settled biomass.

2.4 Analytical methods

TOC was measured with a Total Organic Carbon analyzer (TOC-V, Shimadzu, Japan). Color measurements were carried out using a spectrophotometer (U-2010, Hitachi, Japan) to measure the absorbance of the sample at the peak wavelengths of the dyes used (472 nm and 481 nm for Poly S119 and Orange II dye, respectively). The concentration of dyestuff was calculated from a calibration curve of 'absorbance versus concentration' and concentration

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values were used for calculations of decolorization efficiency. Mixed liquor suspended solids (MLSS) concentration was measured according to the standard methods [15]. Transmembrane pressure (TMP), as an indicator of membrane fouling, was continuously monitored using a vacuum pressure gauge (GC 61, Nagano keiki Co. Ltd., Japan). 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.

3. Results and Discussion

3.1 Effect of feeding mode and reactor design on $MLSS_{aerobic}$ concentration

Although the increase in MLSS concentration has often been reported to have a mostly negative impact on the MBR hydraulic performances [16], controversies exist [17]. Nowadays, information on additional biomass characteristics (e.g., composition and concentration of extracellular polymeric substance) is deemed necessary to furnish a comprehensive picture [2]. In this study, however, dye, poorly soluble starch in high concentration (4.5 g L^{-1}) and fungi together formed extremely gelatinous mixed liquor. Fouling may be mainly attributed to this originally sticky mixed liquor; and, in this context, MLSS concentration can be considered as an appropriate indicator of fouling propensity in this study.

In our previous study on the development of a submerged membrane fungi reactor [9], optimized fouling mitigation techniques allowed stable operation even up to a MLSS

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concentration of 55 g L^{-1}. However, in that system intensive sludge-growth was encountered due to the high dose of starch (carbon source) as required for maintaining the viability of the fungi. Hence, formulation of an improved reactor-design enabling minimization of excess sludge-growth and facilitating fouling prevention by maintaining optimum MLSS concentration in contact with the membrane was deemed imperative.

In this study, in accordance with our expectation, adoption of a reactor design with a settling zone along with split-mode feeding 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^{-1} depending on the feeding mode (**Table.2**). Introduction of whole of the media from the top of the reactor led to massive increase in $MLSS_{aerobic}$ (25 g L^{-1}), 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^{-1}). The specific impacts of different $MLSS_{aerobic}$ concentrations on the fouling of the different modules explored in this study have been elaborated in the following sections. It is worth-mentioning here that a feeding strategy involving splitting 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 a moderate $MLSS_{aerobic}$ (**Table.2**).

3.2 Comparative assessment of the obtained modules

3.2.1 Chemical cleaning applied after high TMP build-up

The modules with rigid and thin spacer along with the unmodified one were directly submerged into the reactor and corresponding rises in transmembrane pressure (TMP) in the course of operation were monitored (**Fig. 3**). The $MLSS_{aerobic}$ concentration was maintained around 5 g L^{-1} during this investigation.

The unmodified module (without spacer) was subject to massive intrusion of sludge. TMP against this module rose up to 90 kPa within one day of start of operation. *In situ* chemical cleaning (3000 mg Cl L^{-1}, 500 ml m^{-2}) only slightly reduced the TMP and high TMP build-up occurred again just on the next day of cleaning. Accordingly, its operation was discontinued. The modules with spacer, on the other hand, were very effective in resisting intrusion of sludge. The module having thin spacer exhibited no rise in TMP until day 35, after which a sharp rise up to 45 kPa was observed. *In situ* chemical cleaning (3000 mg Cl L^{-1}, 500 ml m^{-2}) was effective to reinstate the original TMP. However, absence of chemical cleaning from the beginning may have resulted in gradual build up of sludge within the module, which could not be completely removed by cleaning applied only following development of very high TMP. Consequently, henceforth, sharp rise in TMP was inevitable. Conversely, the module with rigid spacer sustained for comparatively shorter period, and more importantly, chemical cleaning could not recover its original state. This may be attributed to its excessive compactness (owing to the presence of the rigid spacer), which restricted wash-out of the trapped foulants through its bottom end (**Fig.4**). Accordingly its use was ceased. This initial part of the study divulged the superiority of the modules having spacer over the unmodified one.

3.2.2 Periodic chemical cleaning from the start

Investigation carried out under the same $MLSS_{aerobic}$ concentration of 5 g L^{-1} (as mentioned in section 3.2.1), but applying periodic chemical cleaning with a reduced dose (3000 mg Cl L^{-1}, 100 ml m^{-2}, twice/week) from the beginning, revealed no increase in TMP against the thin spacer module for an observation period of 2 months (**Fig.5**). This observation, when

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compared to that depicted in section 3.2.1, indicated that periodic low-dose cleaning from the initiation of operation is preferable to application of high-dose cleaning after severe fouling has already occurred.

The 'hybrid module' was introduced during the subsequent investigation which aimed at performance-assessment of the modules (thin spacer and hybrid) during continuous operation under progressively increasing $MLSS_{aerobic}$, with periodic chemical cleaning (3000 mg Cl L^{-1}, 100 ml m^{-2}, twice/week) applied from the beginning. The modules exhibited comparable performances in the lower $MLSS_{aerobic}$ range. However, the hybrid module appeared to be more resilient against sludge intrusion under the higher $MLSS_{aerobic}$ (~10 g L^{-1}) range, in which the thin spacer module, despite *in-situ* chemical cleaning, demonstrated frequent very high TMP build-up (**Fig. 6**). Autopsy of the thin spacer module revealed its clogged bottom end as well as substantial sludge intrusion within and minimal surface-deposition on it. In contrast, non-destructive visual observation of the hybrid module performed by carefully taking it out of the reactor revealed its cleaner bottom end (suggesting lower intrusion of sludge and efficient backwashing of trapped sludge through this end) and moderate surface deposition (**Fig. 7**). The superior performance of the hybrid module may have rooted from its optimum rigidity due to the presence of the rigid mesh around it, which efficiently restricted intrusion of sludge (improvement over thin spacer module), but was also flexible enough to allow wash-out of the trapped foulants (improvement over rigid spacer module).

Previous studies reported on optimum fiber packing-density under different operating conditions [6-8]. For instance, Yeo et al. [7] recommended that packing density should be kept below 30% to avoid severe interstitial fouling. In this study, the fiber packing densities

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of the explored modules ranged from 53% to 61.5% (**Table.1**). However, the overall rigidity 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 resistance to sludge intrusion of the hybrid module surpassed that of the other modules under high $MLSS_{aerobic}$ concentration (~10 g L^{-1}). Nevertheless, a tendency of higher TMP build-up in between chemical cleaning cycles could be noticed even for this module as the MLSS concentration approached that value (**Fig. 6**, beyond day 25). Prolonged operation under such condition led to a very high TMP (70 kPa). *In-situ* chemical cleaning with a higher dose than usual (3000 mg Cl L^{-1}, 500 ml m^{-2}) could only partially reduce the TMP (50 kPa). Thick surface deposition was observed at this point (**Fig.8**). The fact that the TMP could be reinstated to its original value (3 kPa) by *ex-situ* surface-cleaning with water-jet (**Table.3**) confirmed that surface fouling, unaffected by applied chemical cleaning, was responsible for such high TMP. Evidently, the spacer efficiently prevented sludge intrusion within the module; however, the rejected sludge accumulated on the surface and it was not appropriately scoured-off by the applied aeration in presence of higher MLSS concentration.

3.3 Mitigation of surface fouling

Judging from the extremely sticky nature of the sludge accumulated on the surface of the hybrid module (section 3.2.2), it was considered that only increasing the intensity of the main diffuser of the reactor would not constitute a sound solution to the surface-fouling problem; rather it may cause unnecessary consumption of costly aeration.

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Following explorations of different diffuser-arrangements, a special aeration device was finally designed to appropriately clean the membrane-surface with effective utilization of air. As mentioned earlier, the hybrid module was obtained by winding a rigid spacer on the surface of a module having thin spacer within it. Five steel pipes (1 mm diameter) were attached on the surface of this module. The bottom ends of these pipes were bent in the form a 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 (flexible) spacer (**Fig.9**). Air introduced from the top ends of those pipes hence effectively cleaned the membrane-surface. This specific arrangement of the aeration device enabled efficient utilization of the applied air solely for the cleaning purpose by minimizing escape of air-bubbles to the surrounding media. Thus the designed aeration device was different from just an additional usual kind of diffuser mounted in the close vicinity to the module.

Intermittent aeration (intensity=2.5 L min^{-1}, duration=1 min per 30 min) using the above-mentioned device in addition to the continuous aeration through the main diffuser of the reactor, along with periodic chemical cleaning (3000 mg Cl L^{-1}, 100 ml m^{-2}, 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^{-1} by manipulating feeding mode, even though the chemical-cleaning dose and aeration intensity were gradually reduced to 500 mg Cl L^{-1} and 1 L min^{-1}, respectively (**Fig.10**).

In this study, the rigid spacer module was too rigid to allow wash-out of trapped sludge through its bottom end. On the other hand, under high MLSS concentration (~10 g L^{-1}) the thin spacer module was subject to massive intrusion of sludge and negligible surface-deposition. The hybrid module exhibited superior resistance to sludge-intrusion. However, the rejected sludge deposited on its surface and caused massive surface fouling that was mitigated by utilizing an efficient surface-aerator.

3.4 Performance of the developed module within a pre-filtration cage

Our previous study [9], conducted with an aim to mitigate fouling of commercially available hollow-fiber bundles, reported the efficiency of a coarse-pore pre-filtration assembly in avoiding direct deposition of sludge onto membrane and minimizing inter-fibral deposition of sludge—two factors which eventually lead to fatal fouling. In this study we have demonstrated the superiority of a newly developed hollow fiber module with spacer over that of usual hollow fiber bundles under severe operating conditions. The developed module without the aid of any pre-filtration facility could be operated for prolonged period under high $MLSS_{aerobic}$ concentration. Nevertheless, utilization of a pre-filtration cage in association with the developed module may allow further flexibility in terms of requirement of frequency and dose of cleaning. Further investigations were hence carried out to assess the performance of the developed module with spacer when placed into a cage of coarse pore non-woven mesh (50-200μm).

During this observation, the $MLSS_{aerobic}$ concentration in the reactor was maintained around 20 g L^{-1}. In the case of utilization of a pre-filtration facility, the surface fouling of the pre-filtration facility itself, and not that of the membrane module, becomes critical. Therefore, in this part of the study the surface-aerator as described in section 3.3 was attached on the surface of the pre-filtration cage instead of placing it on the membrane (**Fig.11**). It is worth-mentioning here that, as expected, under the high $MLSS_{aerobic}$ concentration, pre-filtration cage was severely fouled within two weeks or so in absence of additional air-scouring to clean its surface (**Fig.12**). On the other hand, intensive dispersion of the fine-particulate sludge settled within the cage occurred when a diffuser was placed within the cage. This led to aggravated surface-fouling of the membrane module. However, with the specifically designed aerator placed on the surface of the pre-filtration cage, no increase in TMP was observed.

The additional advantage of using a pre-filtration facility in association with the developed module was evidenced by the facts that lower surface-aeration intensity and less frequent chemical cleaning with lower doses (surface aeration=0.5 L/min^{-1}, 1 min per h; chemical cleaning=250 mg Cl L^{-1}, 100 ml m^{-2},once/week) could be allowed when the pre-filtration device was utilized (**Fig.12**). It is likely that very efficient utilization of supplied air for membrane cleaning occurred due to the placement of the bent part of the aeration-pipes in between the coarse-pore cage and the nylon mesh wrapped around it (**Fig.11**). In addition, the relatively smooth surface of the coarse-pore pre-filtration cage may have facilitated its efficient cleaning even by the lower intensity aeration. Conversely, the requirement of milder chemical cleaning of the membrane may be attributed to its exposure to the lower sludge-load owing to the pre-filtration. **Table. 4** lists the comparative advantages of operations with a bare hybrid module and the same module within a pre-filtration cage. It appears that there exists a site-specific scope of choice between the two options depending on the selected operational parameters.

It is worth-mentioning here that, due to the requirement of low-dose chemical cleaning and, more importantly, owing to the possibility of instantaneous dilution within the cage before

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dispersion to the mixed-liquor, the pre-filtration cage may be more beneficial in terms of minimizing direct exposure of the microbes to the cleaning chemical. Dose-specific adverse effect of membrane-cleaning chemical (NaOCl) on biological activity has been previously reported [18]. In our study, removal performance was affected by membrane-cleaning chemical (**Table.2**) under limiting nutritional condition that existed when all the feed was introduced through the sludge-bed,. Detailed discussion on this aspect is, however, beyond the scope of this paper.

It is interesting to note that although comparatively frequent chemical cleaning was proposed in this study, owing to the utilized low dose the total chemical consumption was in fact much lower than that used in full scale plants. For instance, with the lowest chemical cleaning dose utilized in this study (250 mg Cl L^{-1}, 100 ml m^{-2}; once/week), the total NaOCl consumption in three months would be one-nineteenth of that recommended by the membrane supplier for its commercialized polyethylene hollow-fiber modules (3000 mg Cl L^{-1}, 2L m^{-2}) during one prescribed cleaning every three months (**Table.5**).

4. Conclusions

Long-term investigations carried out in a submerged membrane fungi reactor treating high strength industrial effluent revealed the excellent fouling prevention capacity of novel hollow-fiber modules with spacer. The specific conclusions drawn from this study are listed below:

- Under similar conditions, while the usual hollow-fiber bundles exhibited fatal cake-layer fouling within a day or so, the modules with spacer sustained stable performance for a month.

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- Periodic low-dose cleaning from the initiation of operation is preferable to application of high-dose cleaning after severe fouling has already occurred.
- Among the explored modules, a hybrid module (fiber packing density =61.5 %, surface area=1.07 m^2) obtained by winding a rigid spacer (thickness=1 mm, opening=7 mm x 7 mm) on the surface of a module originally containing a thin spacer (opening=1 mm x 1 mm) exhibited the optimum compactness so as to minimize intrusion of sludge while simultaneously allowing wash-out of the small amount of sludge trapped within it.
- Periodic *in situ* chemical backwashing with a low dose (500 mg Cl L^{-1}, 100 ml m^{-2}, twice/week) and intermittent surface-cleaning with a specially designed aeration device (1 L air min^{-1}, 1 min per 30 min) enabled stable operation for a prolonged period under the selected average flux (7.64×10^{-6} m^3 m^{-2} s^{-1}) and MLSS concentrations (up to 25 g L^{-1}).
- Under the similar conditions, fourfold reduction in total consumptions of both chemical and air was possible when the developed module was placed within a coarse-pore (50-200μm) pre-filtration cage. However, a threefold reduction in compactness (membrane area per unit volume of composite module) was inevitable in this case.
- The hybrid module showed stable performance irrespective of the MLSS concentrations (up to an observation range of 25 g L^{-1}). However, for high strength wastewater, it would be worthwhile to consider some strategy to maintain an optimized MLSS concentration with direct contact of the membrane so as to further improve the ease of fouling mitigation. A reactor-design with a settling zone, and a feeding mode comprising split of the influent through the settling zone (40%) and from the top (60%) were proposed with such an aim.

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However, this study was conducted with modules with a fixed size under a selected low flux. Hence, further studies on optimization of the developed module in terms of different design parameters (like length and diameter of fiber, geometry, thickness and pore size of spacer, fiber-spacer arrangement, maximum allowable diameter of the module etc.) as well as optimization of the operational parameters (e.g., flux) are deemed imperative.

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Fouling resistant compact hollow-fiber module with spacer for submerged membrane bioreactor treating high strength industrial wastewater

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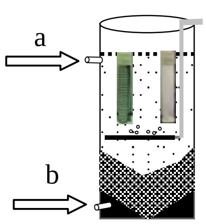
TABLES

Table 1. Specifications of the modules utilized

Module type	Characteristics		
	No. of fibers[a]	Membrane surface area,m^2	Fiber packing density[b], %
Usual bundle	2760	0.97	56
Thin spacer	3045	1.07	61.5
Rigid spacer	2646	0.93	53
Hybrid	3045	1.07	61.5

[a] The same hydrophilically treated polyethylene fibers having a pore-size, outer diameter and effective length of 0.4μ m, 540μm and 208mm, respectively, were utilized in all the modules.
[b]Overall rigidity of the modules, governed by the type and arrangement of the spacers, varied in the following order: rigid>hybrid>thin>usual

Table 2. Effect of feeding mode on $MLSS_{aerobic}$ and removal performance



Feeding mode, %		Avg.$MLSS_{aerobic}$, g/L	Avg. removal performance, %	
a	b		Color	TOC
0	100	4	57.5[c]	54.1[e] -94[f]
100	0	25	93.2[c]	97
60	40	11	91.3[c]-97[d]	97

[c]Acid Orange II dye, [d]Poly S119 dye (higher biosorption)
[e,f] with and without chemical wash of membrane

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Table 3. TMP variation during different cleaning attempts following severe surface fouling of hybrid module in absence of surface aeration

Status	TMP, kpa
Fouled	70
In-situ chemical backwashing	50
Ex-situ water-jet washing	3[a]

[a]Severe fouling occurred again after returning the membrane to the reactor

Table 4. Comparative advantages/disadvantages of utilization of pre-filtration facility in association with the developed module ($MLSS_{aerobic}$~20g L^{-1}, avg. flux $7.64x10^{-6}$ $m^3m^{-2}s^{-1}$)

Criteria	Hybrid module (1)	Hybrid module within cage (2)	Comment
Removal performance	--	--	Similar contribution as a filtration device towards total removal
Compactness (Membrane area per unit volume of module)	Module volume = 0.35 L	Total volume= 1.05 L	Pre-filtration assembly reduces compactness
Chemical cleaning dose (Cl)	500 mg L^{-1}	250 mg L^{-1}	Less concentrated dose required in (2)
Chemical cleaning frequency	Twice/week	Once/week	Less frequent in (2)
Additional surface aeration	1 min per 30 min @ 1 L min^{-1}	1 min per hr @ 0.5 L min^{-1}	More efficient utilization of aeration in (2)
Exposure of microbes to cleaning chemical	Direct exposure	10 times dilution before microbial contact	Pronounced adverse effect of cleaning chemical may be encountered under nutrient-deficient condition

Table 5. Comparison of chemical (NaOCl) consumption for cleaning of commercial and developed modules

Module	Cleaning Frequency	Concentration (mg Cl L^{-1})	Dose (L m^{-2})	Consumption (mg Cl m^{-2} d^{-1})
Developed				
No prefiltration	Twice/week	500	0.1	14.29
With prefiltration	Once/week	250	0.1	3.57
Commercial[a]	Once/3 month	3000	2	66.67

[a] Horizontally mounted polyethylene module from Mitsubishi Rayon [2]

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FIGURES

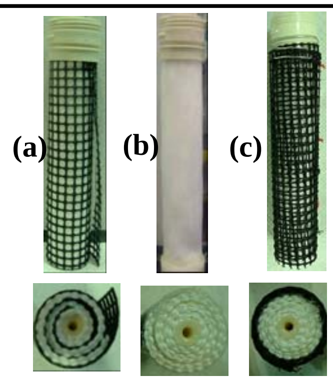

Fig. 1 Side and bottom views of modified modules
(a) Rigid spacer, (b) Thin spacer, (c) Hybrid module (Rigid mesh wound around 'module b')

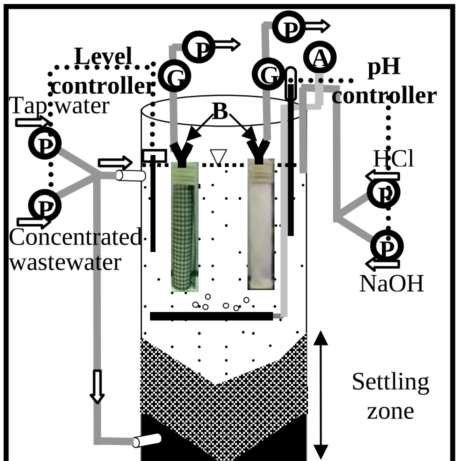

Fig.2 Schematic of laboratory setup (**A**: Air pump, **B**: Backwash, **G**: Vacuum gauge, **P**: Pump)

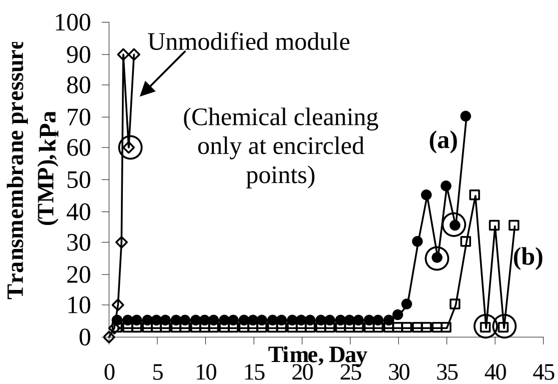

Fig.3 TMP variation during continuous operation under $MLSS_{aerobic} = 5\ gL^{-1}$ [a,b: refer to fig.1; Chemical cleaning with 3000 mg Cl L^{-1}, 500 ml m^{-2}]

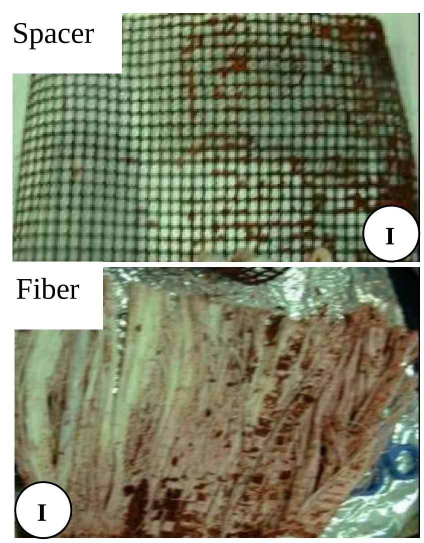

Fig.4 Incomplete wash-out of sludge trapped within over-rigid module 'a' (rigid spacer). Refer to fig.3. 'I': inner part

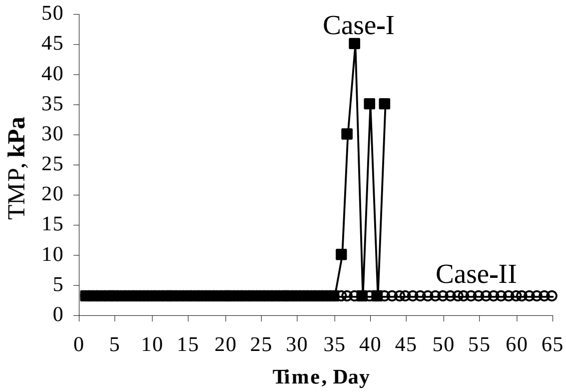

Fig.5 TMP variation against thin spacer module ('b' in Fig.1) with chemical cleaning applied only after high TMP build-up (case-I, 3000 mg Cl L^{-1}, 500 ml m^{-2}) and cleaning applied periodically from start (case-II, 3000 mg Cl L^{-1}, 100 ml m^{-2}, twice/week). $MLSS_{aerobic}$ = 5 g L^{-1}

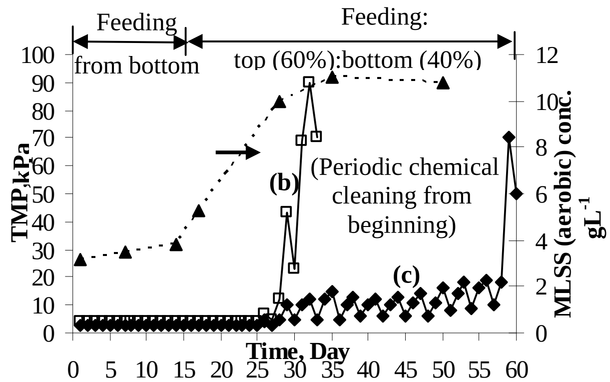

Fig.6 TMP variation during continuous operation under increasing $MLSS_{aerobic}$ [b,c: refer to fig.1; Chemical cleaning with 3000 mg Cl L^{-1}, 100 ml m^{-2}, twice/week]

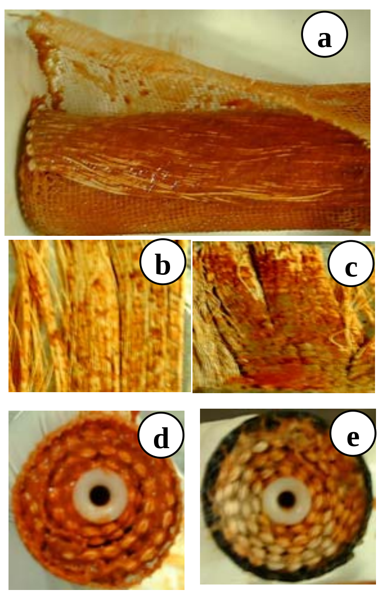

Fig.7 Sludge intrusion within thin spacer module during operation under higher $MLSS_{aerobic}$ (refer to fig.6) a: side view, b: fouled inner fibers (top end), c: fouled inner fibers (bottom), d: clogged bottom end, e: cleaner bottom end of *hybrid* module

Fig.8 Surface fouling of hybrid module in absence of surface-aerator during prolonged operation under high $MLSS_{aerobic}$ (only a few pockets of white fibers visible).

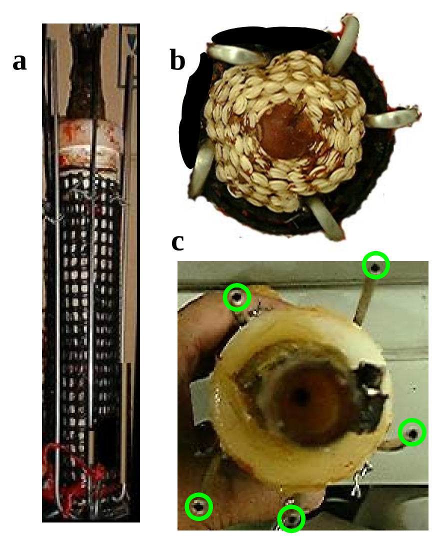

Fig.9 Surface aerator attached on hybrid module. a: side view, b: bottom view, c: top view (air inlets encircled)

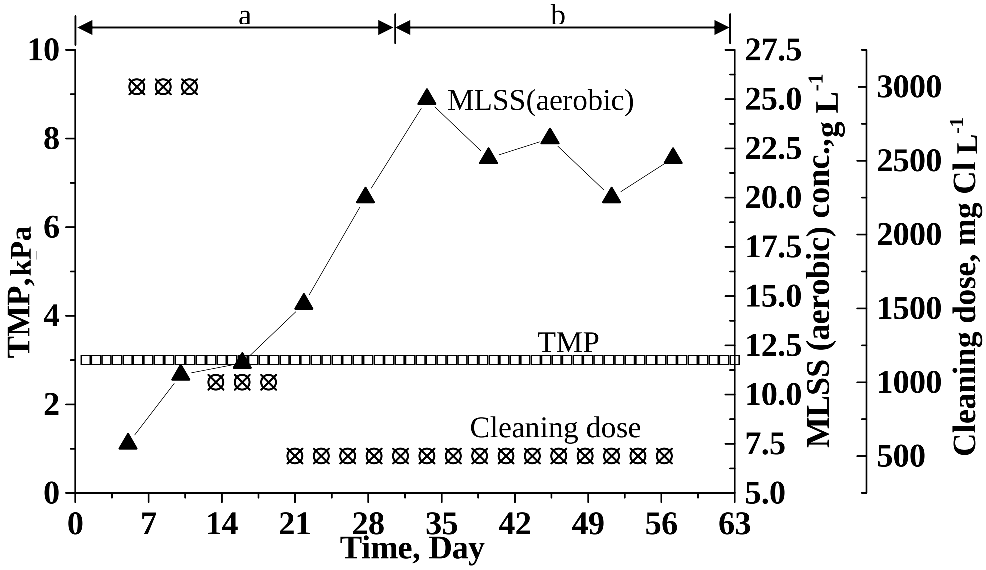

Fig.10 Performance of hybrid module under periodic chemical cleaning (100 ml m^{-2}) and intermittent (1min per 30 min) surface aeration [surface aeration intensities in period 'a' and 'b' were 2.5 and 1 L min^{-1}, respectively].

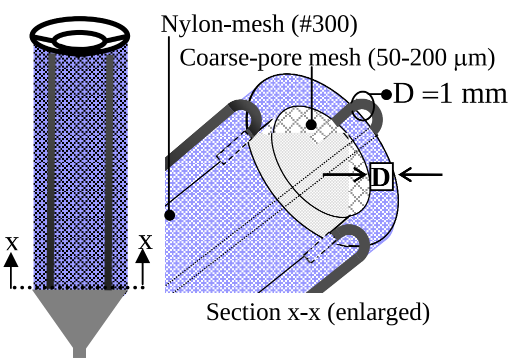

Fig.11 Schematic of pre-filtration cage (Aerator attached on surface)

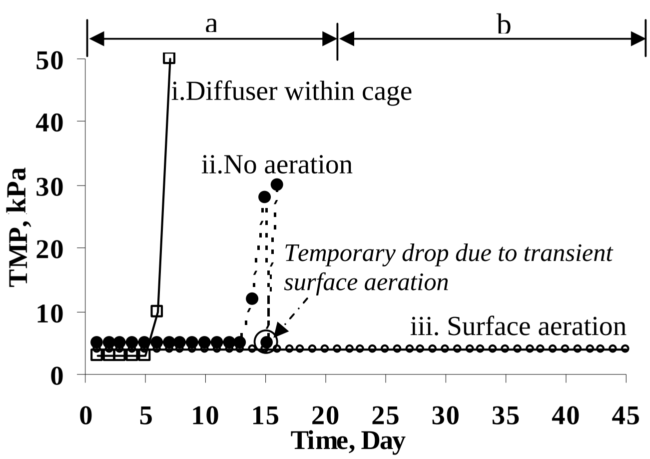

Fig.12 Performance of hybrid module within pre-filtration cage under different aeration schemes. $MLSS_{aerobic}$~20g L^{-1}. [flux (m^3 m^{-2} s^{-1}), cleaning dose (mg Cl L^{-1}), cleaning frequency (per week), aeration intensity (L min^{-1})] =[7.64x10^{-6}, 500, 2, $1]_{period-a}$; [1.53x10^{-5}, 250, 1, $0.5]_{period-b}$.