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Performance evaluation of conventional membrane bioreactor and moving bed membrane bioreactor for synthetic textile wastewater treatment

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ABSTRACT

In this study, conventional membrane bioreactor (MBR) and moving bed-membrane bioreactor (MB-MBR) processes were compared in synthetic textile wastewater treatment. For this purpose, the bioreactors were operated as a conventional MBR, an MB-MBR with a biocarrier filling ratio of 20 % and an MB-MBR with a biocarrier filling ratio of 10 %, respectively. In the conventional MBR operation, 93.1 % chemical oxygen demand (COD) and 87.1 % color (Reactive Red 390) removal efficiencies were obtained. In both MB-MBR operations, almost equal COD and color removal efficiencies were found as 98.5 % and 89.5 %, respectively. Moreover, offline physical and chemical membrane cleaning processes were applied every other day and every 15 days throughout the conventional MBR operation, respectively, while no physical or chemical membrane cleaning was required during both MB-MBR operations. Furthermore, lower polysaccharide concentrations of extracellular polymeric substances (EPS) and floc sizes of sludge and higher zeta potential of sludge were determined in MB-MBR. Considering the obtained results, it may be stated that the MB-MBR process is an attractive treatment technology for reducing membrane fouling propensity for treatment of textile wastewater.

1. Introduction

The textile industry significantly affects the economic development all over the world [1]. In this industry, a huge amount of water is used during the operations of dyeing, sizing, finishing, several washing processes and rinsing cycles. The generated wastewater contains several chemicals such as acids, alkalis, hydrogen peroxide, dyes, surfactants, starch, soaps of metals and dispersing agents [2] and is characterized in high suspended solids (SS), chemical oxygen demand (COD), color, salts and heavy metals [3]. Therefore, it may be accepted as one of most polluting industries in terms of both the high volume and composition of its wastewater [4]. Due to the highly toxic and complex composition of textile wastewater, appropriate treatment is required before discharging it into a receiving environment [3].

Reactive, direct, disperse, acid, basic, azoic and sulfur dyes are used in dyeing process in the textile industry. Some of them (e.g. azoic, disperse and sulfur dyes) are insoluble in water, and their separation from the effluent is easy. However, direct, reactive, acid and basic dyes are excessively soluble in water, and their removal from the effluent is quite difficult by conventional separation techniques. Reactive dyes are some of the most frequently used dyes in the textile industry, however they cannot be reused after their application as they become non-reactive due to hydrolysis [5]. Several treatment methods, such as physical (coagulation-flocculation [6,7], adsorption [8,9] and filtration techniques such as nanofiltration (NF), ultrafiltration (UF) and reverse osmosis (RO) [10,11]), advanced oxidation processes [12], biological treatments [13–15] and their combinations may be applied for textile wastewater in order to achieve discharge standards [1]. Biological treatment processes are an environmentally friendly and economical approach in comparison to physico-chemical treatments due to ensuring complete degradation of contaminants without producing concentrated secondary waste [3].

Membrane bioreactor (MBR) is a promising technology which combines biological treatment and membrane processes [16]. MBR processes have several advantages such as small footprint, lower sludge production, low maintenance, consistency in effluent water quality independent of sludge properties in the bioreactor and higher removal of organic matters, nutrients and persistent organic pollutants in comparison to conventional activated sludge (CAS) processes [16–18]. However, one of the most significant disadvantages is membrane fouling in MBR processes, because it reduces both water quality and quantity and increases the operating costs by 60 % [16,19,20]. The membrane fouling

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phenomenon is very complicated and it generally occurs in forms of foulant adhesion/deposition [21–23] and thermodynamic filtration resistance of gel/cake layer [24,25]. Several factors affecting fouling such as mixed liquor properties, membrane characteristics, hydraulic conditions of the reactor, operational style, temperature and biochemical kinetic parameters [16,26,27].

The moving bed membrane bioreactor technology (MB-MBR) has been recently used as an alternative to overcome membrane fouling in bioreactors [28]. The MB-MBR system combines biofilm processes and suspended biomass inside the submerged MBR for biofilm growth [29]. It was reported that this technology could improve MBR performance and reduce the effects of MLSS on membrane fouling, providing optional strategies to mitigate membrane fouling and fouling propensity [28,30]. In the MB-MBR process, different growth media (carriers) such as polystyrene beads, polyurethane cubes, polyethylene carriers (Kaldnes), granular or powdered activated carbon, blasted clay granules, zeolite, sponge and synthetic biocarriers have been tested in submerged MBR [31]. It should be considered that biocarriers must have a low cost, high porosity for microbial immobilization and good mechanical strength for fouling control [32].

Today, MBRs have been widely used for textile wastewater treatment due to their higher performance for COD, color and other pollutant removal in comparison to conventional activated sludge processes [15,17]. Jegatheesan et al. [17] and Yang et al. [33] reported in their reviews that COD and color removal efficiencies were found to be between 80–98% and 70–100%, respectively, for treatment of textile wastewater by MBR. Mixed liquor suspended solids (MLSS) concentrations in MBR varied between 4 g/L and 15 g/L in most of the studies, and MBRs were operated between 0.1 to 0.5 bar TMP values. Membrane flux values were also varied from 5 to 30 L/m^2.h in these studies [17]. On the other hand, the MB-MBR process has been a relatively novel technology for textile wastewater treatment [33]. However, to the best of our knowledge, there had been only one study about printing and dyeing wastewater treatment by the MB-MBR process [34].

The aim of this study was to compare the MBR and MB-MBR processes for textile wastewater treatment in terms of both pollutant removal and membrane fouling. Within this framework, COD and color removal efficiencies were measured to determine the pollutant removal performances of MBR and MB-MBR. Furthermore, several observations and analyses were performed representing membrane fouling and filtration characteristics such as transmembrane pressure (TMP), EPS species and concentrations, particle size and zeta potential analyses of sludge.

2. Materials and methods

2.1. Experimental set-up

The laboratory scale MBR system consisting of a plexiglass reactor with a 5 L working volume was operated as a conventional MBR and moving bed MBR, respectively, throughout the study. A ceramic flat sheet membrane module (Cembrane, Denmark) with a 0.057 m^2 total surface area and a nominal pore size of 0.1 μm was used in the MBR. Fig. 1 shows the schematic presentation of the MBR and MB-MBR (after addition of biocarriers). Initial seed sludge was taken from a municipal wastewater treatment plant in Istanbul. Oxygen was supplied with a stainless-steel air diffuser located at the bottom of the reactor with an air pump. The dissolved oxygen concentration in the reactor was kept above 3 mg/L. The temperature of the mixed liquor in the reactor was kept constant 20 ± 1 °C by a recirculating pump in the heat jacket of the reactor. The reactor was fed with synthetic textile wastewater adapted from Yurtsever et al. [35] and the composition of the feed wastewater is shown in Table 1. Reactive Red 390 dye used in this study produced in Chroma (Shanghai) Chem-Tech Co. Ltd. named as Colorsal Brillant Red MF-3GL. It is highly soluble and also biodegredable. A stock solution of Reactive Red 390 (10 g/L) was prepared and added in the required amount to the synthetic textile wastewater after the acclimation period of the operation. The biocarriers were hollow cylinders with dimensions of 16.75 mmø x5 mm manufactured by WARDEN Biomedia Bioflo+. The biocarriers had a density of 170 kg/m^3, and the total and protected surface areas were 1036 and 800 m^2/m^3, respectively.

Table 1
Feed synthetic textile wastewater characteristics.

Added ingredient	Concentration (mg/L)
$C_6H_{12}O_6.H_2O$	1000
$NaHCO_3$	1000
NH_4Cl	230
K_2HPO_4	37
KH_2PO_4	67
$CaCl_2.2H_2O$	4
$MgCl_2.6H_2O$	3.4
$FeSO_4.7H_2O$	5.92
$MnSO_4.H_2O$	0.4289
$ZnSO_4.7H_2O$	0.1053
Na_2SO_3	0.2811
$CuSO_4.5H_2O$	0.0556
$NiSO_4.6H_2O$	0.1
$CoCl_2$	0.5457
Reactive Red 390	10

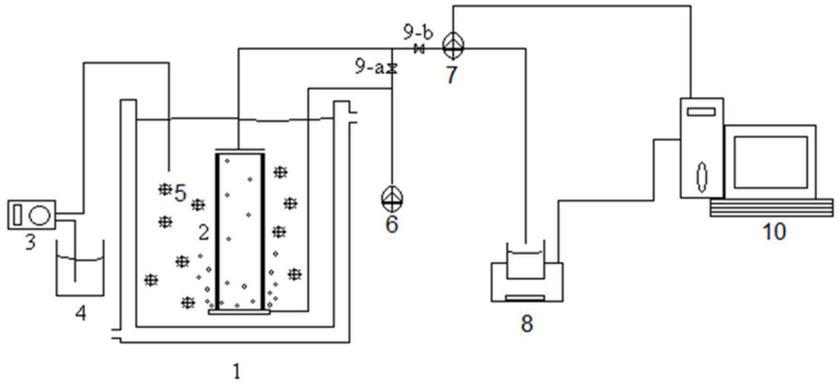


Fig. 1. MBR system used in the study (1- reactor, 2- flat sheet ceramic membrane, 3- peristaltic pump, 4- feed tank, 5- bio-carriers, 6-air pump, 7- Vacuum pump, 8- analytical balance, 9-a ile 9-b- automated valve, 10- computer).

2.2. Operating conditions of MBR and MB-MBR

The reactor was operated at a constant permeate flux under a sludge retention time (SRT) of 30 days. SRT was controlled by discharging certain amount of sludge throughout the study. In the whole operation period, an intermittent filtration cycle with 30 min suction followed by 30 min relaxation was applied to control membrane fouling. The operational conditions of the MBR and MB-MBR are provided in Table 2. In the first period, the bioreactor was operated as a conventional MBR without biocarriers for about 103 days. After completion of studies with the conventional MBR, certain proportions (20 % v/v) of fresh carriers were filled into the reactor, and an additional 37 days of operation was carried out in the MB-MBR (Period 2). On the 142nd day of the operation, half of the biocarrier material in the MB-MBR was taken from the reactor, and the third operation phase was started (10 % v/v). The MB-MBR was operated this way for another 35 days (up to day 177; Period 3). Average pH values of feed wastewater and activated sludge in MBR were 8.05 ± 0.40 and 7.54 ± 0.61, respectively.

2.3. Membrane cleaning

In all MBR and MB-MBR operations, constant flux was drawn, and the change in the TMP value was recorded online by an automation panel. In the first period, the conventional MBR was operated until TMP reached 0.6 bars, and then, membrane cleaning was applied physically and/or chemically. The chemical ceramic membrane cleaning procedure was performed according to the method described by Jin et al. [36] when the effectiveness of physical cleaning decreased. After the first period, the TMP value in the MB-MBR decreased approximately by half in comparison to the conventional MBR, and it varied between 0.3 to 0.4 bars throughout the MB-MBR operation. There was no need for physical or chemical membrane cleaning during the MB-MBR process.

2.4. Analytical methods

Permeate samples were collected to analyze COD and color. The measurements of COD in the influent wastewater and the effluent, as well as MLSS and MLVSS in the reactor systems, were performed according to the Standard Methods [37]. The color of the influent and effluent was measured at a wavelength of 455 nm using a Hach Lange DR 5000 spectrophotometer. The pH, dissolved oxygen (DO) and temperature were monitored daily in the MBR and MB-MBR using a WTW Multiline P4 multimeter (SenTix 41 pH probe and CellOx 325 DO probe).

The analyses of soluble EPS (S-EPS), loosely-bound EPS (LB-EPS) and tightly-bound EPS (TB-EPS) of the activated sludge in the MBR and MB-MBR were determined according to the EPS extraction procedure adapted from Liu et al. [38], Zhou et al. [39] and Xiao et al. [40]. In this procedure, 15 mL of the waste sludge was centrifuged (4000 × g at 4 °C) for 15 min, and supernatant was collected as S-EPS. The sludge pellet left in the tube was then re-suspended by adding 15 mL of NaCl solution (0.05 %). After that, the re-suspended sample was sheared by applying a vortex and incubated in a water bath (70 °C) for 1 min. The supernatant in the centrifuge tubes was then collected as LB-EPS after the second centrifugation (4000 × g) at 4 °C and 10 min. The residual pellet was re-suspended to the initial volume (15 mL) by adding NaCl solution (0.05 %) and incubated in a water bath (60 °C) for 30 min. The mixture of sludge was again centrifuged (4000 × g at 4 °C) for 15 min, and the supernatant was taken from the tubes as TB-EPS. The concentrations of polysaccharide (PS) and protein (PN) were determined by the phenol-sulfuric acid method [41] and Lowry method [42] after the extractions.

The floc size distribution of the activated sludge in the MBR and MB-MBR under steady-state conditions was measured by a Malvern Hydro 2000MU Mastersizer. The zeta potential of the sludge samples was measured using a Malvern Nano ZS Zetasizer.

3. Results and discussion

3.1. Performances of MBR and MB-MBR

The bioreactor was operated as a conventional MBR for 55 days at SRT 30 days without Reactive dye 390. After the 55th day of the operation, Reactive Dye 390 was added into the synthetic textile wastewater, and the bioreactor was operated for additional 50 days as a conventional MBR. The COD and color concentrations of raw synthetic textile wastewater were found 857.2 ± 10.5 mg/L and 505.3 ± 3 Pt-Co. pH values were mesaured 8.077 and 8.145 in feed wastewater with and without dye. COD concentration of feed wastewater increased approximately 9 ± 7.5 mg/L after the addition of Reactive Dye 390. On the 104th day of the operation, biocarriers were added to the MBR to cover 20 % of the total reactor volume, and the second period of the operation started. On the 142nd day of the operation, half of the biocarriers in the MB-MBR were taken from the reactor, and the third period started (10 % biocarrier/reactor volume). The MB-MBR was operated in these conditions for another 35 days (up to day 177). The COD and color removal efficiencies in each period are shown in Fig. 2. The COD removal efficiencies were determined as 93.1 % and 98.5 % for the MBR and each period of the MB-MBR, respectively. The effluent COD concentrations were found to be 62.1 ± 40 mg/L, 12.3 ± 5.9 mg/L and 15.4 ± 6.7 mg/L in each successive period, respectively. On the other hand, 87.1 % color removal efficiency was achieved in the first period of the operation. The color concentration in effluent was found as 66.2 ± 9 Pt-Co throughout the MBR operation. An average of 89.2 % and 88.90 % color removal efficiency was achieved in the next two periods (period 2 and 3) where the biocarriers were added in the amounts of 20 % and 10 % (v/v). The effluent color values were also determined as 62.6 ± 11.6 Pt-Co and 56.68 ± 4.4 Pt-Co in periods 2 and 3, respectively.

Aerobic MBRs have been investigated by several authors for treatment of synthetic textile wastewater [14,15,43,44]. Konsowa et al. [15] investigated synthetic textile wastewater containing red dye CI81 and they found COD removal rates between 90.9%–95.6% at 1−3 g/L of

Table 2
Operational conditions of MBR and MB-MBR.

Period	Type of reactor	Conditions	Operating condition	Duration (days)
1	MBR	Without dyes and biocarriers Added 2.5 mg/L and 5 mg/L Reactive Dye 390, respectively Added 10 mg/L Reactive Dye 390	SRT (days): 30 HRT (h): 16.9 Net Flux (L/m^2.h): 5.01	1−54 55−71 72−103
2	MB-MBR	Added 20 % volume of bio-carriers /total working volume of MBR	SRT(days): 30 HRT (h): 16.54 Net Flux (L/m^2.h): 5.47	104−141
3	MB-MBR	Added 10 % volume of bio-carriers /total working volume of MBR	SRT(days): 30 HRT (h): 15.25 Net Flux (L/m^2.h): 5.83	142−177

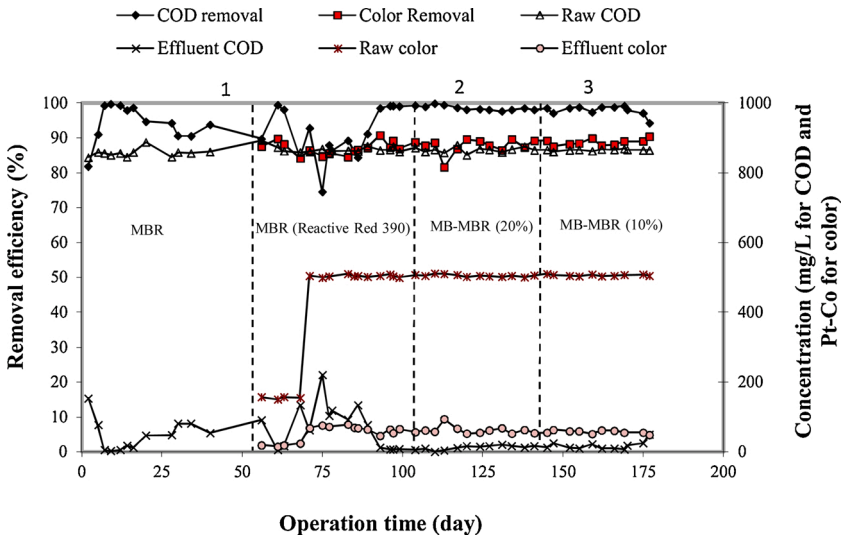


Fig. 2. COD and color removal efficiencies and the concentration of COD and color of raw wastewater and effluent in MBR and MB-MBR over time.

MLSS concentrations. Deowan et al. [43] also investigated synthetic textile wastewater and 90 % COD removal efficiency and between 20–50% color removal efficiencies were obtained at 12 g/l MLSS and 0.5 bar of TMP at a constant pressure mode of MBR operation. Synthetic textile wastewater treatment was also investigated by Friha et al. [44] and COD and color removal efficiencies were found 98 % and 100 % at a constant pressure mode of MBR operation (0.07−0.35 bar). Yurtsever et al. [14] researched treatment of textile wastewater containing 1000 mg/L COD and 100 mg/L Remazol Brilliant Violet 5R, and they found 97 % COD removal and partial color removal efficiencies (between 30–50%) at 20 LMH of membrane flux.

There are several studies which investigated moving bed bioreactors (MBBR) for textile wastewater treatment in the literature [45–48]. Park et al. [45] researched anaerobic-anaerobic-aerobic (A2O) MBBRs by using polyurethane-activated carbon foam carriers (20 % v/v) for textile wastewater treatment. In the study, 86 % of COD removal was obtained after the 8th day of operation. However, they reported that a coagulation process is required to achieve an effective treatment [45]. Castro et al. [47] also investigated the combined treatment of textile wastewater with Reactive Orange 16 using ozonation and MBBR. The COD and color removal efficiencies were found as 90 % and 97 %, respectively. It was noted that the color was not removed by MBBR, but it was mainly removed in the ozonation process [47]. MBBR performance was also investigated for pretreated textile wastewater treatment with the Fenton oxidation process by Francis and Sosamony [48]. The authors reported that the maximum COD removal efficiency was obtained at the 67.06 % filling ratio of carriers.

Although the MB-MBR process has been a promising technology, there is only one study in the literature which investigated textile wastewater treatment [34]. In the study, a combination of anaerobic-aerobic MBBR-MF processes was investigated for treatment of simulated textile wastewater containing azo dye reactive brilliant red X-3B. The COD and color removal efficiencies were found as 85 % and 90 % at the filling ratio of polyethylene biocarriers of about 35 % (v/v). It was also reported that the color was mainly removed in the anaerobic conditions [34].

3.2. Variation of MLSS and EPS concentrations

Variations of the concentrations of MLSS throughout the MBR and MB-MBR operations are presented in Fig. 3. The initial MLSS concentration in the bioreactor operated as a conventional MBR was around 1120 mg/L. The MLSS concentration increased gradually to around 7050 mg/L within 54 days. After the 54th day, Reactive Red 390 was added into the synthetic wastewater, and MLSS concentrations decreased slightly to around 6280 mg/L until the 71 st day. After adaptation of the activated sludge to Reactive Red 390, the MLSS concentrations increased sharply to 10,490 mg/L at the 90th day of the operation. The biocarriers were added with a filling ratio of 20 % (v/v) into the MBR on the 103rd day, and then, the MLSS concentration

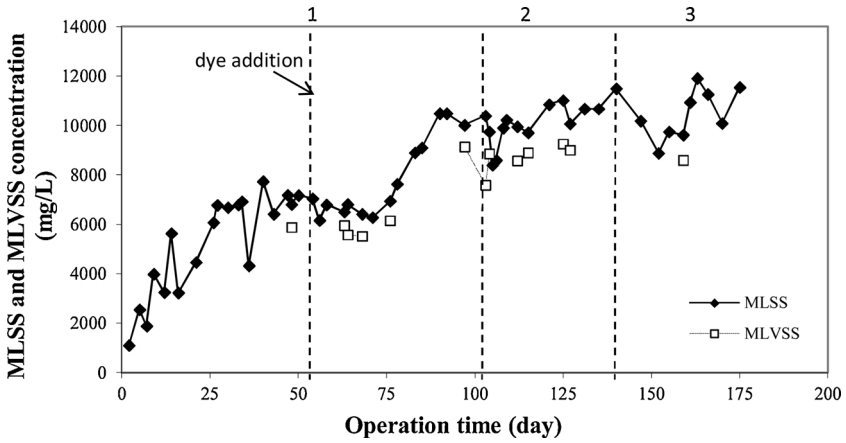


Fig. 3. The concentrations MLSS and MLVSS throughout the operation.

slightly decreased to around 8400 mg/L, and then increased again to around 10,220 mg/L at the 109th day of the operation. The MLSS concentration remained between 9720 and 11,030 mg/L until the last period of the MB-MBR operation. In the last period, the MLSS concentrations decreased again to 8890 mg/L due to the fact that half of the bio-carrier material in the MB-MBR was taken from the reactor, and the third operation phase started (10 % biocarrier / reactor volume). The MLSS concentrations then remained again between 10,950 and 11,910 mg/L in the last period. In the study, significant accumulation of activated sludge into the biocarriers was not observed. This could be related to the holes of the biocarriers which are relatively large for MLSS to accumulate. Throughout the operation, the MLVSS/MLSS ratios were found between approximately 82 % and 92 %.

As known, soluble and bound parts of EPS are important constituents in membrane fouling in MBRs [49]. The variations of the protein fraction of S-EPS, LB-EPS and TB-EPS are presented in Fig. 4. As seen in Fig. 4, the PN concentrations of S-EPS increased from around 20 mg/L to 60 mg/L immediately after adding Reactive Red 390, and they remained around 20 mg/L again after the 76th day. Furthermore, the PN concentration of LB-EPS increased immediately after addition of Reactive Red 390, similar to the PN fraction of S-EPS, and then decreased until the 104th day of the operation. According to these results, addition of the biocarrier into the MBR led to an increase in the PN concentration of LB-EPS. The PN concentrations of TB-EPS decreased over time, while 165.85 mg/L was detected on the 40th day of operation, and it partially increased after addition of Reactive Red 390, then continuing to decrease again. Although the PN concentrations of TB-EPS increased sharply after addition of the biocarriers on the 104th day of the operation, they mainly decreased throughout the MB-MBR operations.

The PS concentrations of S-EPS, LB-EPS and TB-EPS are shown in Fig. 5. In terms of the PS fractions of EPS, Reactive Red 390 addition at the 54th day of the operation did not significantly affect the PS concentration except for TB-EPS. Additionally, as seen in Fig. 5, addition of the biocarriers into the MBR did not influence PS concentrations, unlike the PN fractions of EPS.

Fig. 6 shows the protein and polysaccharide concentrations of soluble microbial product (SMP) in permeate throughout the operation. The concentrations of protein and polysaccharide varied between 3.05–5 mg/L and between 2.95–6.3 mg/L during the conventional MBR operation, respectively. The average protein and polysaccharide concentrations were found as 4.06 mg/L and 3.17 mg/L during the 2nd period (MB-MBR operation with 20 % biocariers). In the last period (MB-MBR operation with 10 % biocariers), the mean protein and polysaccharide concentration was found to be 3.4 mg/L and 2.22 mg/L, respectively. According to the obtained results, SMP concentrations decreased in MB-MBR operation compared to conventional MBR. As it is known, SMP in supernatant (namely S-EPS in the study) concentrations play a significant role in membrane fouling, especially internal fouling. In terms of membrane fouling mechanisms, SMP cause membrane pore blockage by the adsorption of SMPs pore walls [50]. Additionaly, the SMP is easily accumulated in MBR, due to membrane rejection and leads to poor filterability of the mixed liquor. Moreover, polysaccharide of SMP contributes to membrane fouling more than protein [51]. In the study, higher protein rejections (90.6 %, 74.2 % and 81.3 % for periods 1, 2 and 3) in SMP were obtained compared to polysaccharide rejections in SMP (80.5 %, 62.1 %, 70.9 %, respectively).

Duan et al. [52] investigated the characteristics of EPS and SMP in moving bed bioreactor-membrane bioreactor (MBBR-MBR), and they operated 4 reactors namely a conventional MBR (with SS recycle), an MBBR-MBR with the media fill ratio of 36.7 % (without SS recycle), an MBBR-MBR with the media fill ratio of 26.7 % (with SS recycle) and an MBBR-MBR with the biocarrier fill ratio of 20.0 % (with SS recycle). A lower total membrane resistance and no obvious fouling were found in the MBBR-MBR with the carrier fill ratio of 26.7 %. More significant fouling was observed in the MBR and MBBR–MBR with lower and higher media fill ratios. Lower EPS and SMP (S-EPS) concentrations were also determined in both conventional MBR and MBBR-MBR with the media fill ratio of 26.7 % [52]. Fu et al. [53] also reported that the better filtration performance that was obtained in the MB-MBR process in comparison to conventional MBR could be primarily due to the lower EPS concentration, mainly lower polysaccharide concentrations.

3.3. Variation of particle size and zeta potential of sludge

In the study, analyses on the distribution of particle size and zeta potential of the activated sludges were conducted for all periods of operation at steady-state conditions. Figs. S1 and S2 show the particle size distribution and zeta potential distribution of the sludge samples. As it may be seen in Table 3, the d10, d50 and d90 floc sizes of the sludge particles were determined as 6.133 μm, 27.584 μm and 79.314 μm in the conventional MBR operation without a biocarrier. After the filling of biocarriers into the MBR in period 2, the d10 floc size increased from 6.133 μm to 6.597 μm, while the floc sizes of d50 and d90 decreased by 32.6 % and 53.9 %, respectively. On the other hand, the d10, d50 and d90 floc sizes increased slightly in the MB-MBR operation with a biocarrier fill ratio of 10 % (period 3) in comparison to the MB-MBR with a biocarrier fill ratio of 20 % (period 2). Similar results were observed in other studies, and it was stated that the mean floc size was higher in conventional MBR compared to MB-MBR [31,54]. The surface weighted mean values and vol. weighted mean values of the particle sizes in the MB-MBR with biocarrier fill ratios of 20 % and 10 % suggested that continuous collision of biocarriers may be responsible for the break-up of activated sludge flocs. However, this break-up phenomenon of flocs was not serious keeping in view decreases of 40 % and 37 % in vol.

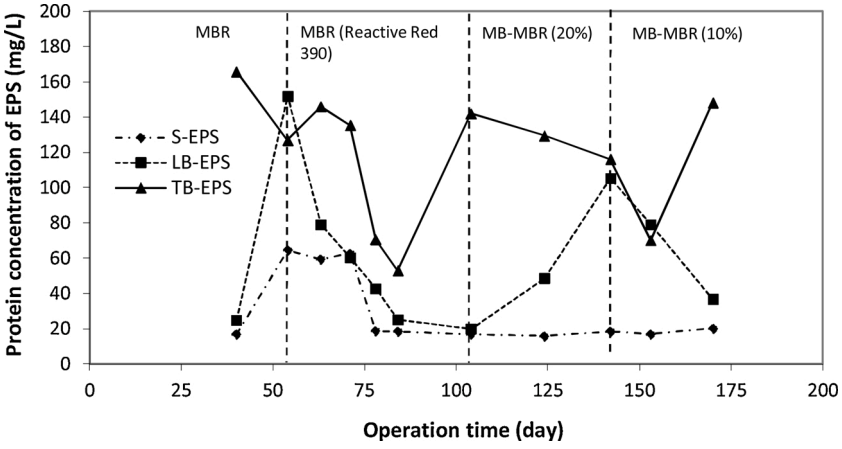


Fig. 4. Variations of protein concentrations of S-EPS, LB-EPS and TB-EPS throughout the operation.

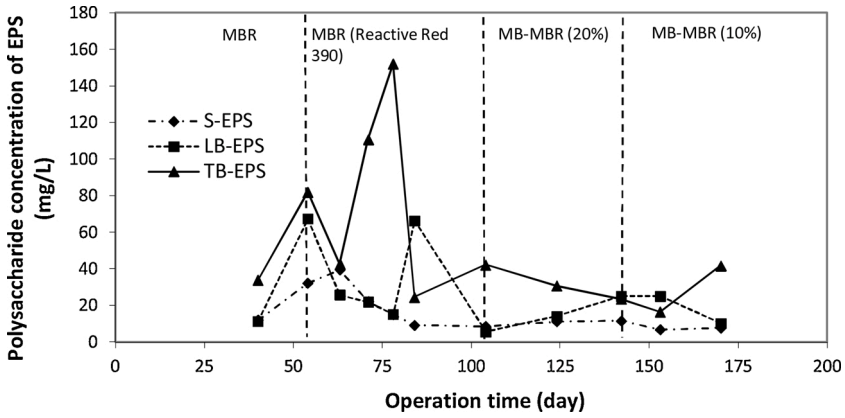


Fig. 5. Variations of polysaccharide concentrations of S-EPS, LB-EPS and TB-EPS throughout the operation.

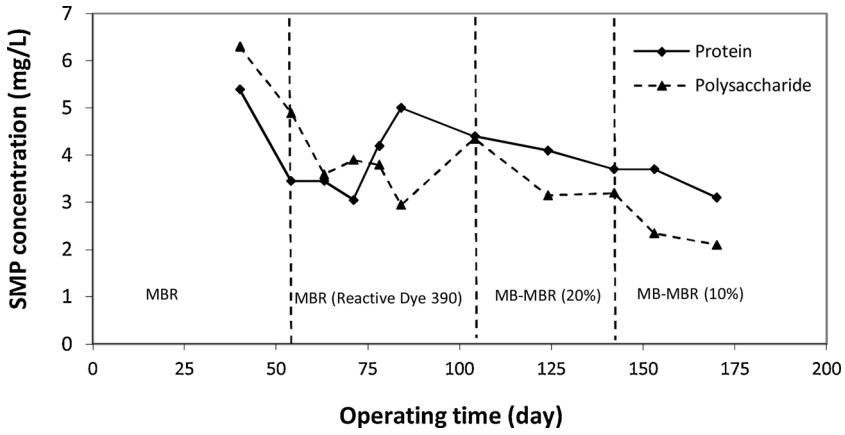


Fig. 6. Variations of protein and polysaccharide concentrations of SMP in permeate throughout the operation.

Table 3
Particle sizes of sludge samples at steady-state conditions.

Period	D(0.1) (μm)	D(0.5) (μm)	D(0.9) (μm)	Surface weighted mean (μm)	Vol. weighted mean (μm)
1	6.133	27.584	79.314	14.766	35.602
2	6.597	18.502	36.543	13.226	21.166
3	6.884	19.709	39.276	13.922	22.265

Table 4
Mean zeta potential values of sludge samples at steady-state conditions.

Periods	Zeta potential (mV)	Std deviation (mV)
1	−20.8	4.69
2	−20.5	5.30
3	−17.3	3.87

weighted mean particle size in the MB-MBR with biocarrier fill ratios of 20 % and 10 %, respectively.

The zeta potential values of the sludge samples in each period were found as -20.8 mV, -20.5 mV and -17.3 mV, respectively (Table 4). The obtained results showed that addition of biocarriers positively increased the zeta potential values of the sludge samples. Deng et al. [55] investigated membrane fouling in a sponge-submerged MBR and conventional MBR, and they found a higher zeta potential value (6.85 ± 3.65 mV) in the sponge-MBR in comparison to the conventional MBR (10.50 ± 4.50 mV). Sun et al. [56] investigated membrane filtration performance by a biofilm MBR with biofilm carriers (Kaldnes K1-carrier) and a conventional MBR, and lower zeta potentials were found in the biofilm MBR (-12.3 mV) in comparison to the conventional MBR (-9.7 mV). The authors also reported that the repulsion between sludge particles in the conventional MBR was a little weaker, therefore promoting more flocculation in the conventional MBR than in the biofilm MBR according to the zeta potential values [56].

Liao et al. [57] reported that the zeta potential of activated sludge was affected by EPS concentration, and the PN/PS ratio of EPS was more significant than the amounts of EPS constituents in terms of the zeta potential. On the other hand, it was reported that the protein concentrations of EPS would neutralize the negative charge of sludge flocs [58]. As seen in Figs. 4 and 5, the PN/PS ratios of all types of EPS were found higher in the MB-MBR with biocarrier fill ratios of 20 % and 10 % in comparison to the conventional MBR operation.

3.4. Membrane filtration performances

The variations of TMPs and membrane fluxes throughout the MBR operation with and without biocarriers are presented in Fig. 7. The TMP values increased sharply after the 5th day of the conventional MBR operation, and the first offline physical membrane cleaning was applied with a sponge under tap water and then backwashing at 2 bars with air. After that, the TMP values increased gradually from 0.147 bars to 0.657 bars until the 20th day of the operation. Throughout the conventional MBR operation, severe membrane fouling was observed, and offline physical membrane cleaning was carried out every other day. The first offline chemical cleaning was applied on day 61 when the physical cleaning process was not effectively cleaning the membrane. The membrane fluxes varied between 2.62 and 7.70 L/m^2.h as the membrane was swiftly fouled, and then, the flux decreased with an increase

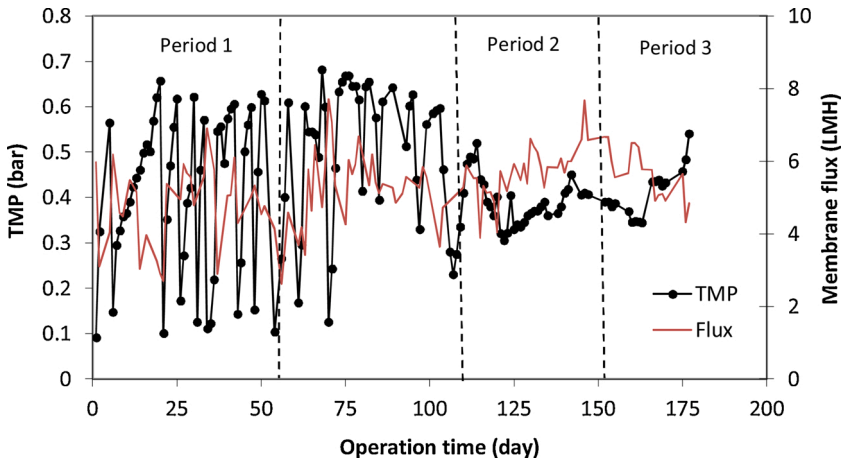


Fig. 7. TMP variations and membrane fluxes throughout the operation.

of the TMP in the conventional MBR operation. The mean membrane flux was 5 L/m^2.h during the conventional MBR operation. As seen from Fig. 7, MBR and MB-MBR were operated with a constant flux mode, however, target flux could not be achieved when the TMP values were above -0.6 bar throughout the operation. Therefore, both membrane flux and TMP values fluctuated simultaneously. Similar observation was mentioned by another researcher [14].

The MB-MBR operation was started with the biocarrier fill ratio of 20 % on day 104, and TMP sharply decreased from 0.596 bars to 0.23 bars. No physical or chemical membrane cleaning was required throughout the MB-MBR operation (period 2). In period 3, no physical or chemical cleaning was applied, similar to period 2; however, the TMP values increased from 0.344 bars to 0.54 bars after the 163rd day of the operation, because routine MB-MBR operation could not be performed due to restrictions imposed because of the novel coronavirus outbreak. The mean fluxes were found as 5.47 and 5.83 L/m^2.h during the MB-MBR operation with the biocarrier filing ratios of 20 % and 10 %, respectively. Looking at previous studies on treatment of textile wastewater in aerobic MBRs, the flux value was kept between 2 and 8 L/m^2.h [44,59–61]. However, higher flux values in treatment of textile wastewater by MBR have also been applied by some researchers [14,15].

The results obtained in this study showed that the MB-MBR process have some advantages over conventional MBR in terms of membrane fouling control. Similar results were also obtained in other studies [53,55,62,63]. Lee et al. [63] reported that addition of biocarriers into an MBR could mitigate membrane fouling by both decreasing MLSS concentrations and creating collisions on the membrane surface. In this study, the MLSS concentrations did not decrease after the addition of biocarriers in the MBR and there was no significant sludge accumulation in the biocarriers. However, as seen from Fig. 7, the TMP values significantly decreased after the addition of biocarriers and there was no need for membrane cleaning throughout the MB-MBR operation. Although biocarriers affect the concentration of soluble part of EPS in MBR, it can be said that it had significant effects on physical collisions with the ceramic membrane and TMP was, therefore, reduced. Fu et al. [53] found cake layer fouling could be a dominant fouling mechanism both in MBR and MB-MBR processes; however, they also reported that membrane fouling arising from cake layer formation could be controlled and mitigated by the scouring effect of biocarriers in the MB-MBR process.

4. Conclusions

In this study, a conventional MBR and an MB-MBR were compared in terms of both COD and color removal efficiencies and membrane fouling propensities for treatment of textile wastewater. The bioreactor was operated as a conventional MBR and an MB-MBR with different biocarrier filling ratios (20 % and then 10 %). The removal efficiencies of COD and color were found to be almost equal for all operation periods. The mean COD removal efficiencies during the MBR and MB-MBR operations were determined as 93.1 % and 98.5 %, respectively. While 87.1 % color removal efficiency was achieved in the first period of the operation, a mean value of 89.5 % color removal efficiency was obtained in both MB-MBR operations with the biocarrier filling ratios of 20 % and 10 %. Additionally, the TMP values in the MB-MBR operation decreased approximately by half in comparison to the conventional MBR. In terms of the EPS concentrations, the polysaccharide concentrations of EPS decreased, while the protein concentrations increased in the MB-MBR in comparison to the conventional MBR. Furthermore, lower average floc sizes and higher zeta potential values were obtained in the MB-MBR in comparison to the conventional MBR. Considering the obtained results, it was determined that the MB-MBR reduced the propensity of membrane fouling and provided stable and lower TMP values in the operation.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jwpe.2020.101631.

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