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Low-Cost MBR For Sewage Treatment As Non-Conventional Water Resource

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Abstract

Egypt suffers from water scarcity, therefore non-conventional water resources are needed to secure increasing water demand in the various development processes especially agriculture sector which consumes 85% of the water budget. Well- treated sewage water represents a good source for land irrigation that is an alternate solution for environmental disposal of the treated sewage. In this study, a cloth-media membrane bioreactor (MBR) was designed, manufactured and evaluated for sewage treatment at different operating conditions. Cloth-media filter with 0.553 m^2 effective filtration area was submerged in an aeration tank with 50 L theoretical working volume and 44.5 L effective working volume. The system was operated for three different Hydraulic Retention Time (HRT) and two different dissolved oxygen (DO) concentration. The HRTs are 4, 6 and 8 hours while dissolved oxygen concentrations were 4.5 mg/l and 2.3 mg/l. Sludge residence time (SRT) was maintained at 29.7 days by removing 1.5 L from the mixed liquor suspended solids (MLSS) on daily basis. The system operation showed significant impact of the DO concentration and HRT on the treatment performance with higher efficiency at higher DO concentration and longest HRT. At high DO concentration, the range of residual concentrations was 10.4-20.3 mgCOD/L and 4.2-10.1 mgBOD/L while at low DO concentration the ranges were 17.5-30.1 mg COD/L and 7.6-14.8 mg BOD/L. Both DO concentration and HRT have significant impact, directly or indirectly, on the membrane fouling. Economically, the system operation at low DO concentration (2 ppm) and medium HRT (6 hrs) was found cost-effective, sustainable and provided treated effluent complying physico-chemically with reuse standards.

Keywords: Cloth-media, MBR, sewage, non-conventional water resource, effluent reuse, membrane fouling.

1. Introduction

Water scarcity is the most significant challenge for the Egyptian governments to secure basic needs of the population. Poor water resources management strategies and unaffordable safe and effective wastewater treatment systems associated with limited coverage with sanitary services cause contamination of irrigation water with associated health risks and environmental problems [1-3]. WHO, 2022 [4] reported that in 2020, 46% (3.58 billions) of the world's population do not have safely managed sanitation services and around 10% of the global population eats food irrigated with wastewater since 45% of the global domestic sewage is discharged without safe treatment. Effective sewage treatment followed by safe reuse improves water quality, ecosystem function and reduce land application of artificial fertilizers which reduces acceleration and control of climate change and improve soil fertility [5]. Increasing demand for more stringent effluent quality standards during the last decades in both developed and developing countries led to rehabilitation and/or upgrading of many existing wastewater treatment plants.

Membrane Bioreactor (MBR) has been developed and extensively studied for advanced wastewater treatment. The MBR system is defined as a promising technology for municipal wastewater treatment and has prospective role in fostering sustainable water reuse in arid countries and water scarcity regions [6]. MBR is an integrated activated sludge system with membrane filtration [7]. The membrane filtration replaces final clarifiers to separate final treated effluent from the MLSS.

There are two basic MBR process configurations; external or side-stream and internal or submerged

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MBR. In the external MBR, the mixed liquor is pumped from the aeration tank to the membrane at flow rates that are 20–30 times the product water flow to provide adequate shear for controlling solids accumulation at the membrane surface.

The high cost of pumping makes this type impractical for full-scale municipal wastewater treatment plants. In the submerged MBR process, the membrane is submerged directly in the aeration tank and by applying low vacuum pressure, treated effluent is driven through the membrane leaving the MLSS or biomass in the aeration tank. The MBR has excellent treatment performance which makes effluent reuse safe, secure and sustainable alternate for environmental disposal of the treated effluent [8]. The MBR has potential to attain superior effluent quality with very low total suspended solids (TSS) concentration and turbidity which may reach less than 2 ppm and 1 NTU, respectively [9, 10]. Also COD and BOD concentration could be as low as 10 mg/L for COD and less than 5 mg/L for BOD [11, 12].

This makes effluent from the MBR is adequate for many water reuse applications with little residual chlorine disinfection for subsequent distribution.

High MLSS concentration in the MBR systems enables higher treatment performance for high strength municipal and industrial wastewater at short Hydraulic Retention Time (HRT). The MBR is a robust technology with small footprint and can sustain higher MLSS concentration, longer SRT and less sludge production with lower sensitivity to peak flow, load and finally consistent effluent quality [6]. The MBR has smaller footprint and provide better effluent quality over the conventional activated sludge processes [13, 14]. Long SRT and high concentration of MLSS enable the MBR system to effectively remove pharmaceutical residues better than the conventional activated sludge systems [15, 16]. Regarding effluent quality the MBR technology is more reliable than media filters, oxidation ponds and constructed wetlands for sewage treatment and effluent reuse [17].

History of the MBR technology in China indicates technical advantages and public policy towards water resources and environmental protection as the main driving force for moving from lab and pilot scale MBR system to the commercial application [18].

The disadvantages associated with the MBR are mainly cost related. MBR technology is characterized by high capital cost due to expensive membrane units and high-energy costs due to the pressure gradient. Membrane fouling problem can lead to frequent cleaning of the membranes, which stop operation and require clean water and chemicals [19]. The membrane fouling causes unstable operation of the MBR system [20] and declines water production and increases maintenance and operation cost of the system [21, 22]. Low temperature during the winter has negative impacts on sludge activity and deterioration of the sludge filterability since there is a clear link between the low activity and fraction of colloidal and soluble constituents with the increase in the trans-membrane pressure [23]. Formation of dense and compact cake layer which act as secondary filtration layer was observed in a gravity-driven MBR operated under air scouring and continuous filtration mode [24]. The dense cake layer and longer HRT have significant effect on percentage removal of COD [24]. The membrane fouling represents the bottleneck of the MBR technology and makes operation of the MBR costly high for sustainable treatment of wastewater [25]. A gravity-driven MBR (G-D MBR) is defined as low-cost MBR system and has received increased attention as reliable decentralized wastewater treatment system due to stable permeate flux [26] without chemical cleaning [27] and its lower energy consumption [28, 29]. The G-D MBR is characterized by low flux rate which represents the drawback of the system comparing to the typical MBR system [30, 31]. During the last few years, membrane-based wastewater treatment shows great competitiveness and strong potential for effective treatment and effluent reuse [18]. However, membrane fouling limits its widespread application for municipal wastewater treatment. Membrane fouling causes decline in the volume of produced water and successive chemical cleaning of the membrane reduces its lifespan [32]. Physical creation of best hydrodynamic conditions is applicable by air scouring, dynamic MBR and/or moving porous media [33] Integration of biofilm reactors like moving bed biofilm and fixed bed biofilm with the MBR has significant positive impact on the treatment performance and consistency of the flux rate [17, 34]. Increase in the transmembrane pressure (TMP) is mostly linked to the membrane characteristics and bio-fouling cakes. Estimated energy requirement for operation of the full-scale MBR is ranged between 0.5 and 1 kWh/m^3 and increase of the TMP due to bio-fouling accounted for 30-70% of the energy requirement. Control of membrane fouling by periodic backwash and chemical cleaning could reduce the energy consumption by 2-8% [14] and frequent replacement of the membrane module is the ultimate solution to overcome buildup of the irreversible fouling. Chemical coagulants were used to control membrane fouling and enhance phosphorous removal in the MBR system [35, 36]. Irreversible fouling which represent part of internal fouling of the membrane pore cannot be removed completely and causes pore constriction [37, 38]. Pore constriction decline restoration of the membrane permeability with continuous decline in the flux by time [39]. New innovative technology using microbes and microbial enzymes was applied to hinder membrane biofilm growth and this technology is called Quorum Quenching (QQ) approach [40, 41]. The QQ is one of the most popular biological methods for control of membrane fouling [42, 43]. Advantage of the biological approaches like QQ is targeting specific single molecules without substantial impacts of the MLSS [44] and so it may have potential real application [45]. However, it is hard to reproduce QQ bacteria in the mixed liquor and represents the biggest challenge for researchers [46].

Aeration and air flow in the MBR system is the main source of energy consumption since temporary increase of TMP should be mitigated by increasing air flow rate to control membrane fouling [6]. Periodic fouling control strategy by air scouring coupled with intermittent filtration significantly improved the flux rate [47, 32]. This control strategy enhances detachment of the fouling layer from the membrane surface [17, 48]. However, application of air scouring at high intensity and frequencies may result in the formation of thin and dense fouling layer which negatively affect the effluent quality and the treatment performance of the membrane [29]. Air scouring coupled with relaxation cause a thin fouling layer with less hydraulic resistance due to the low concentration of extracellular polymeric substance (EPS) while air scouring with continuous filtration causes a thin, dense and compact fouling layer with more hydraulic resistance [24]. Full-scale hollow fiber MBR systems were evaluated to reduce aeration and air scouring energy requirements. System optimization could result in energy reduction within 33% above the conventional activated sludge which has 50% more reactor volume [49]. The system can be optimized to get more reduction in the energy consumption within 20% but ammonia discharge level will be > 0.5 mgN/L. The study indicated possible operation of the MBR system at aeration optimized mode of 1 mg/L and aeration constrained mode of 0.5 mg/L. The well optimized hollow fiber MBR systems consume 4% and 7% more aeration and air scouring energy than IFAS and MBBR, respectively [49].

Development of low-cost MBR is the way to decline capital cost of the MBR system. Cloth-media MBR was designed and assembled as low-cost technology for municipal wastewater treatment [50]. The system was able to provide good quality effluent that meets physicochemical parameters of the unrestricted reuse guidelines in Kingdom of Saudi Arabia and Egypt. Main goals of the current study is the investigation of impact of HRT and DO concentration on the treatment performance and membrane fouling of cloth-media MBR treating municipal sewage under Egyptian conditions.

The goal of this study is to evaluate the performance of a cloth-media membrane bioreactor (MBR) for sewage treatment under different operating conditions (HRT, DO).

2. MATERIAL AND METHODS

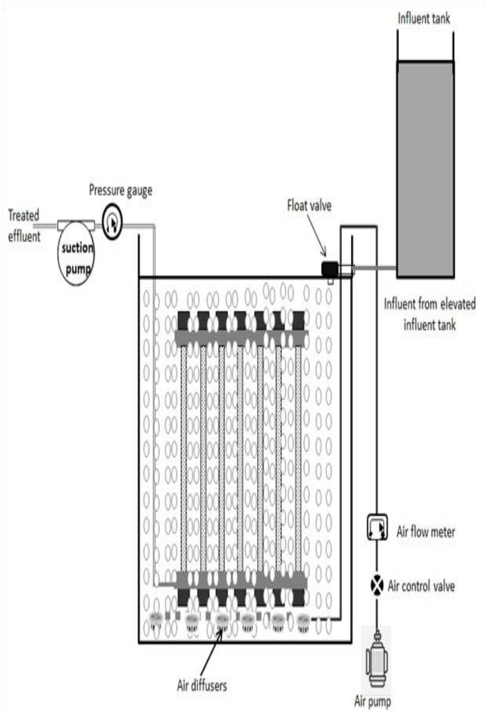
Experimental setup

The research work of the MBR was carried out in a continuous mode at Research Station of Water Pollution Research Department, National Research Center. The experiment was carried out using a cloth media MBR system consists of an aeration tank with 50 L effective volume, float valve, membrane module connected with suction pump, aeration pump, air flow meter, air control valve, pressure gauge, influent tank and effluent receiving tank. Schematic diagram of the treatment system is presented in Figure 1.

Aeration tanks

Three reactors were made of Plexiglas and used as aeration tanks. The reactor or aeration tank has 55.65 liter total volume and 50 liter theoretical working volume while the effective working volume after excluding the volume of the membrane module was

44.5 L. Dimensions of the aeration tank are 50 cm, 21 cm and 48 cm for length, width and effective water depth, respectively. The aeration tank has 5 cm free board. The reactor has a submerged membrane module with 5.5 liter in addition to a float valve for feeding influent wastewater and number of air diffusers installed beneath the MBR module.



Fig(1):Experimental setup of the MBR system

Membrane module

Three membrane modules were made of 28tubes of 316 grade stainless steel mesh tubes with 0.1 mm mesh size for each. Each tube has 33 cm total length, 2 cm diameter and 31.5 cm effective length. The tubes are covered with polyester fabric which acts as filtration media. Effective filtration area of each tube is 198 cm^2 and the total effective area of the membrane module (28 tubes) is 0.553 m^2. The tubes are arranged in 4×7 module and assembled together by polypropylene joints and polypropylene tubes. The tubes have died ends in one side and the other ends of the tubes are connected to the drain line which has a pressure gauge and suction pump. The TMP is continuously measured and readjusted to the desired flux rate by readjusting the flow rate of the suction pump. To maintain the same flux or permeate flow rate in the three reactors at 20.1 $L/m^2.h$, some of the filtration tubes are blocked in the second reactor and third reactor to reduce the effective filtration area of the membrane module.

Table 1 shows the specific operating conditions in the three reactors.The aeration tank is linked to influent feed line coming from an elevated influent tank. The influent line ends with float valve in the aeration tank to control influent flow according to the permeate flow or flux rate. A number of air diffusers are installed beneath the MBR module and connected to an air pump through aeration pipe which has an on/off valve and an air flow meter to control the air flow rate.

Operating conditions

Permeate flux

Operation of the MBR below the critical flux is an effective approach to avoid severe fouling including removable and irremovable fouling within the membrane filtration systems [51]. The critical membrane flux is the maximum flux below which there is no significant increase in the TMP [15]. Most publications of the MBR reported an average membrane flux rate in the range of 17-25 $L/m^2.h$ [52]. In this study, 20.1 $L/m^2.h$ was selected as the permeate flux with continuous operation for 18 minutes suction and 2 minutes off which means that the calibrated suction pump will be operated at 22.33$L/m^2.h$.

Sludge inoculums and influent wastewater

The sludge flocs act as adsorbent material for colloidal part of raw wastewater and so presence of sludge inoculums during the startup is necessary to prevent pore clogging [53]. So at starting up, the reactors were inoculated with activated sludge seed from Gabal Al-Asfar Wastewater treatment plant at 3.5 g TSS/L. On daily basis, 1.5 liter from the MLSS was wasted to keep the SRT at 29.7 days. The MLSS concentration was continuously monitored on daily basis to keep the concentration at 3.5 g/L.

The reactors were fed with raw wastewater after screening. The influent wastewater was enriched with synthetic sewage or diluted with tap water to keep average COD at 500 mg/L as possible by using online storage tank.

The synthetic sewage contains peptone, meat extract, molasses, urea, potassium dihydrogen phosphate, magnesium sulfate, calcium chloride, and sodium chloride. The online storage tank is connected with the aeration tanks via three tube connections ending with three float valves; one in each tank.

Table 1: Operating conditions and data of the MBR systems

Reactor	R 1	R 2	R 3
Total reactor volume, L	55.65	55.65	55.65
Reactor working volume, L	50	50	50
Total volume of membrane module, L	5.5	5.5	5.5
Effective working volume, L	44.5	44.5	44.5
Total number of filtration tube	28	28	28
Number of effective filtration tube	28	19	14
Effective filtration area, m2	0.553	0.376	0.277
Selected permeate flow, L/m2.h	22.3	22.3	22.3
Suction mode, on/off in minutes	18/2	18/2	18/2
Actual permeate flow, L/m2.h	20.1	20.1	20.1
Flux rate, L/h	11.115	7.558	5.568
Hydraulic retention time, hrs	4.0	5.89≈6.0	7.99≈8.0

TMP and membrane cleaning

The TMP was used as indicator of membrane fouling. The TMP was measured on daily basis using online pressure gage with readjustment of the suction pumps to keep the permeate flux constant. Membrane backwash was estimated to be done when the TMP exceeds 0.15 bar while onsite mechanical cleaning was carried out when TMP exceeds 0.25 bar. The membranes were cleaned by back flushing with air and permeate backflow for 2 minutes at air back wash rate of 11 L air/minute and permeate flux backflow of 35 L/m^2.h. The onsite mechanical cleaning was performed by wiping the surface with a soft sponge while suction pump is off. After wiping the surface, the membrane was back flushed with air at 11 L/m for 5 minutes. Gkotsis et al [54] selected 0.4 bar as the maximum TMP in the pilot-scale MBR treating real municipal sewage and chemical cleaning was performed at 0.35 bar. He operated the pilot-scale MBR treating municipal sewage at permeate flux of 13.5 L/m^2.h which is less than the selected value (20.1) in this study. This could be attributed to the higher MLSS concentration (6.5 g/L) used by [54] comparing to the selected value (3.5 g/L) in the current study.

Aeration system

The air diffusers installed beneath the membrane module are two types; coarse bubble diffusers and fine bubble diffusers. The air flow rate in the coarse bubble diffusers is fixed at 20 L/m^2.minute [35, 36] while air flow in the fine diffusers was adjusted to have the desired DO in the aeration tank.

Analytical parameters

Water sampling and lab analysis

Water samples from the influent and treated effluents of the membrane bioreactors were collected three times a week to ensure membrane durability and that the fabrics are not damaged; however, only one sample per week has been fully analyzed. The samples were subjected for analysis of TSS, turbidity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total alkalinity, total Kjeldahl nitrogen, total ammonia nitrogen, nitrate nitrogen and total phosphorous.

Mixed Liquor Suspended Solids (MLSS): The sludge samples were subjected to the analysis of sludge volume, sludge volume index, MLSS and MLVSS concentration using methods 2540 D and 2540 E [55].

All the analytical parameters were analyzed according to APHA, 2017 [55]. COD was measured according to closed reflux colorimetric method (5220 D). BOD was analyzed using 5-day BOD test (5210 B). Total ammonia nitrogen was measured using titrimetric method (4500-NH_3 E) after preliminary distillation step (4500-NH_3 B). TKN was measured using macro-kjeldahl method (4500-N_{org}) followed by distillation step (4500-NH_3 B) and titrimetric method (4500-NH_3 E). Nitrate was measured using salycilate method after suspended solids and color removal. Total phosphorous was measured using vanadomolybdophosphoric acid colorimetric method (4500-P C) after potassium persulfate digestion. Total alkalinity was measured using titration method (2320

B). The pH and dissolved oxygen were measured online.

Statistical analysis

Data was subjected to one way analysis of variance (One- way ANOVA) to check the significant differences between the studied materials regarding the treatment efficiency and membrane fouling.

3. Results and discussions

3.1. Characteristics of raw influent

Analysis of raw influent municipal wastewater enriched (if needed) with synthetic sewage or diluted with de-chlorinated tap water indicated COD, BOD, TKN, ammonia nitrogen and TP average concentrations of 454±20, 227±12.5, 60.1±6.5, 21.4±5.8 and 7.73±0.83, respectively. The treatment performance of the different MBR units at different operating conditions indicated good quality effluent with significant impacts of both DO and HRT on the treatment performance.

3.2. Treatment performance of the reactors

As depicted in Table 2 and 3, all the reactors provided good quality effluent with ranges of the average residual COD and BOD ranges of 20.3-30.1, 14.3-20.2 and 10.4-17.5 mg/l for COD and 10.1-14.8, 6.3-9.8 and 4.2-7.6 mg/l for BOD in the R1, R2 and R3, respectively (Table 2). The corresponding removal ranges are 93.3-95.5, 95.5-96.8 and 96.2-97.7 for COD and 93.5-95.6, 95.6-97.2 and 96.7-98.2% for BOD (Table 3). These values are similar to what has been reported by Banti et al. [56] who operated a lab-scale MBR system treating synthetic sewage (average COD, ammonia and TKN of 890 mg/L, 31 mgN/L and 63 mgN/L, respectively). The authors [56] reported that at feed/microorganism (F/M) ratio of 0.14 gCOD/gTSS.d and DO concentration of 2.5 mg/L treated effluent with residual average COD, ammonia and TKN of 15, 0.06 and 48 mg/L, respectively with corresponding percentages removal of 98.3%, 99.8% and 23.8% is provided. In the current experiment, the F/M ratio in the three reactors are 0.7, 0.5 and 0.4 on average according to the measured flow rates in the reactors indicated better quality than reported ranges by [57].

Statistical analysis for the residual values of the main pollutants and their removal percentages with regard to the DO concentration is shown in Table 2 and 3. The data indicated the significant positive impact of increasing the DO concentration at similar HRT.

For phosphorous removal, high concentration of MLSS in the MBR was reported to enables the system to remove between 70-90% of the TP without chemical coagulant addition [54]. However, Zahid and El-Shafai [50] reported limited TP removal between 51% and 55% in the MBR systems which correspond to volumetric loading rate of the reactor between 11.8 and 13.9 mgTP/L.d. Accordingly metal salts alum and ferric chloride were added to enhance TP removal in the MBR systems with maximum percentage removal of 69% (13.5 mgP/L of the reactor volume per day) and 46.5% after addition of 15 mg/L alum and ferric chloride, respectively [35, 36]. In the current study the TP removal was excellent since percentages removal ranges were 80.5-86.3, 85.5-91.8 and 85.4-92.2%, in R1, R2 and R3, respectively with corresponding volumetric loading rates between 19.68 and 38.1 mgTP/L.d. These values are better than what has been reported earlier [51, 35, 36].

In the current study the total estimated sludge yield at high DO was 0.18, 0.25 and 0.23 g VSS/gBOD removed at HRT of 4, 6 and 8 hrs, respectively .The corresponding values at low DO were 0.19, 0.26 and 0.33 g VSS/gBOD removed.While the observed yield sludge at high DO was 0.095 ,0.137 and 0,173 g VSS/gBOD at HRT 4,6 and 8 hrs , respectively. The corresponding values at low DO were 0.097 ,0.139 and 0.176 g VSS/gBOD. The difference between the total and observed yield is the waste or excess sludge.

Data in Table 4 and 5 represents the statistical analysis of residual pollutants and their removal percentages with regard to the HRTs at similar DO concentration. The data clearly indicated the great significant impact of HRT on the treatment performance and removal of the pollutants.

3.3. Impacts of DO on the TMP and permeate flux at different HRTs

As shown in Table 6a, the high DO concentration at similar HRT non-significantly improves the sludge filterability or declines the membrane fouling as indicated by the values of the TMP and permeate flux; however, there was a clear significant impacts on the frequency of backwashing and onsite mechanical cleaning (Figures 2).

Table 2: Impacts of DO concentration on the treatment performance at different HRT

Parameter	HRT 4 hrs		HRT 6 hrs		HRT 8 hrs	
	High DO	Low DO	High DO	Low DO	High DO	Low DO
COD	20.3±3.2[a]	30.1±2.7[b]	14.3±2.8[a]	20.2±3.4[b]	10.4±1.7[a]	17.5±2.5[b]
BOD	10.1±1.7[a]	14.8±1.5[b]	6.3±1.1[a]	9.8±1.8[b]	4.2±1.1[a]	7.6±1.6[b]
TSS	0.42±0.72[a]	0.42±0.71[a]	0.66±0.42[a]	0.79±0.41[a]	0.25±0.5[a]	0.4±0.9[a]
TKN	9.8±1.6[a]	20.4±2.1[b]	8.2±1.6[a]	13.3±2.2[b]	6.9±1.5[a]	12.1±1.9[b]
Ammonia	3.5±1.0[a]	10.3±1.1[b]	1.3±0.4[a]	10.2±3.0[b]	1.8±1.4[a]	7.5±1.4[b]
No3	21.4±2.5[a]	5.8±2.1[b]	25.1±4.2[a]	10.3±2.3[b]	25.6±3.3[a]	12.4±1.2[b]
TP	1.02±0.11[a]	1.5±0.13[b]	0.66±0.17[a]	1.19±0.15[b]	0.58±0.16[a]	1.1± 0.22[b]

Values at similar HRT and different DO concentration with different superscript letters are statistically significant different

Table 3: Impacts of DO concentration on the % removal of water quality parameters at different HRT

Parameter	HRT 4 hrs		HRT 6 hrs		HRT 8 hrs	
	High DO	Low DO	High DO	Low DO	High DO	Low DO
COD	95.5±0.7[a]	93.3±0.8[b]	96.8±0.6[a]	95.5±0.8[b]	97.7±0.3[a]	96.2±0.5[b]
BOD	95.6±0.7[a]	93.5±0.8[b]	97.2±0.5[a]	95.6±0.9[b]	98.2±0.4[a]	96.7±0.7[b]
TSS	97.1±4.8[a]	97.3±4.3[a]	96.5±7.3[a]	96.9±0.8[a]	96.9±6.2[a]	95.3±11.7[a]
TKN	83.3±3.4[a]	65.7±4.3[b]	86.6±3.2[a]	78.3±3.9[b]	88.1±3.2[a]	79.2±3.7[b]
Ammonia	83.3±7.6[a]	51.5±16.0[b]	93.8±3.3[a]	53.9±15.5[b]	89.7±3.8[a]	55.7±14.0[b]
TP	86.3±1.9[a]	80.5±2.3[b]	91.8±2.5[a]	85.5±1.8[b]	92.2±2.4[a]	85.4±3.0[b]

Values at similar HRT and different DO concentration with different superscript letters are statistically significant different

Table 4: Impacts of HRT on the treatment performance at high DO concentration (4-4.5 ppm)

Parameter	Residual values in mg/L			% removal		
	HRT 4 hrs	HRT 6 hrs	HRT 8 hrs	HRT 4 hrs	HRT 6 hrs	HRT 8 hrs
COD	20.3±3.2[a]	14.3±2.8[b]	10.4±1.7[c]	95.5±0.7[a]	96.8±0.6[b]	97.7±0.3[c]
BOD	10.1±1.7[a]	6.3±1.1[b]	4.2±1.1[c]	95.6±0.7[a]	97.2±0.5[b]	98.2±0.4[c]
TSS	0.42±0.72[a]	0.66±0.42[a]	0.25±0.5[a]	97.1±4.8[a]	96.5±7.3[a]	96.9±6.2[a]
TKN	9.8±1.6[a]	8.2±1.6[b]	6.9±1.5[c]	83.3±3.4[a]	86.6±3.2[b]	88.1±3.2[b]
Ammonia	3.5±1.0[a]	1.3±0.4[b]	1.8±1.4[c]	83.3±7.6[a]	93.8±3.3[b]	89.7±3.8[c]
NO3-N	21.4±2.5[a]	25.1±4.2[b]	25.6±3.3[b]	-	-	-
TP	1.02±0.11[a]	0.66±0.17[b]	0.58±0.16[b]	86.3±1.9[a]	91.8±2.5[b]	92.2±2.4[b]

Values in the same row with different superscript letters are statistically significant different

Table 5: Impacts of HRT on the treatment performance at low DO concentration (1.5-2.5 ppm)

Parameter	Residual values in mg/L			% removal		
	HRT 4hrs	HRT 6 hrs	HRT 8 hrs	HRT 4 hrs	HRT 6 hrs	HRT 8 hrs
COD	30.1±2.7[a]	20.2±3.4[b]	17.5±2.5[c]	93.3±0.8[a]	95.5±0.8[b]	96.2±0.5[c]
BOD	14.8±1.5[a]	9.8±1.8[b]	7.6±1.6[c]	93.5±0.8[a]	95.6±0.9[b]	96.7±0.7[c]
TSS	0.42±0.71[a]	0.79±0.41[a]	0.4±0.9[a]	97.3±4.3[a]	99.6±0.8[a]	95.3±11.7[a]
TKN	20.4±2.1[a]	13.3±2.2[b]	12.1±1.9[b]	65.7±4.3[a]	78.3±3.9[b]	79.2±3.7[b]
Ammonia	10.3±1.1[a]	10.2±3.0[a]	7.5±1.4[b]	51.5±16.0[a]	53.9±15.5[a]	55.7±14.0[a]
No3	5.8±2.1[a]	10.3±2.3[b]	12.4±1.2[c]			
TP	1.5±0.13[a]	1.19±0.15[b]	1.1± 0.22[a]	80.5±2.3[b]	85.5±1.8[a]	85.4±3.0[a]

Values in the same row with different superscript letters are statistically significant different

The averages of TMP were 0.118±0.088, 0.108±0.068 and 0.094±0.047 bar at 4hrs, 6hrs and 8hrs HRT of high DO level versus 0.132±0.089, 0.120±0.079 and 0.104±0.052 at low DO concentration, respectively. Also the average values of the permeate flux were 18.9±2.8, 19.4±1.0 and 20.0±1.2 $L/m^2.h$ at high DO concentration versus 18.7±2.4, 19.2±2.5 and 19.7±1.3 $L/m^2.h$ at low DO concentration at 4-hrs, 6-hrs and 8-hrs HRT respectively.

In the current study there was no big differences between the two DO levels (2.3 and 4.5 mg/L) which might be the reason to have non-significant positive impacts of high DO concentration on the TMP and permeate flux. These values are similar to the data obtained by Gkotsis et al [54] who reported that the DO concentration of the aeration tank in the range of 2-3 mg/L was maintained in pilot-scales MBR systems treating real municipal wastewater without negative impacts on the membrane fouling and process performance since the residual COD and ammonia concentration were in the range of 10-25 mg/L and less than 0.1 mg/L, respectively. It was reported that Low DO concentration promotes excessive growth of filamentous bacteria that was detrimental to the system performance and membrane fouling by enhancing excessive secretion of EPS which causes severe membrane fouling[58]. On the other hand, Gkotsis et al [54] reported that Low DO concentration in the re-circulated activated sludge (0.3 mg/L) did not negatively affect the membrane fouling.

However, diminishing the DO concentration enhances denitrification process and contributes significantly in filamentous growth and reduce concentration of colloids and positively improve membrane fouling .Similarly, Wang et al [31] reported positive impact of the filaments abundance in the membrane fouling of the submerged MBR. Soluble microbial products (SMP) and colloids were considered as the main fouling agents in the membranes in the MBR systems [54].

This could be attributed to the little role of the fine air bubbles on the detachment and removal of cake layer. It is well known that the coarse air bubbles play the most important role in mitigating the membrane fouling comparing to the fine air bubbles or diffused air [59]. Combined effects of both dissolved oxygen and hydraulic retention time are highly significant with maximum flux rate and minimum fouling potential at highest HRT and higher DO concentration. Since the raw influent is kept more or less constant, the hydraulic retention time subsequently affects the F/M ration which represents the more important factors in the process controls and operation of the biological activated sludge. Low F/M ratio at higher HRT declines accumulation of colloidal particles and intermediate metabolites from the microbial hydrolysis of the substrate.

3.4. Impacts of HRT on the TMP and permeate flux

HRT was found more significantly affecting the TMP and permeate flux at similar DO concentration but it is more effective in the HRTs with more gaps., the TMP and permeate flux in case of 6 hrs HRT have no significant differences with 4 hrs and 8 hrs (Table 6b). However, the TMP and permeate flux at 8 hrs HRT were significantly better than the values at 4 hrs HRT (Table 6a Figure 2b). These results are confirmed by many research works that elaborate the controlling role of the organic loading rate or F/M ration on the MBR performance and fouling potential. Adjustment of operating conditions like F/M ratio, HRT and DO concentration plays a significant role in control of membrane fouling [56]. Separation between the aeration tank and membrane tank with low F/M ration was considered beneficial in reducing the SMP (protein and carbohydrates) at low concentration (less than 6 mg/L) which declines the fouling potential of the membranes [54]. Also, the authors reported that the presence of pre-denitrification tank significantly reduced the F/M in the following aeration tank and membrane tank which result in mitigating membrane fouling by keeping SMP at low concentration (<10 mg/L).

Other researchers found that, the high F/M ratio promotes more SMP and more bound EPS which result in less sludge filterability [60] since the low DO concentrations enhance growth of filamentous bacteria in the activated sludge [61, 62]. However, filamentous bacteria were manipulated in pilot-scale MBR to effectively control membrane fouling [63, 64]. On the other hand there was no correlation between SMP and EPS and proliferation of filamentous bacteria [65] but has important impacts on the flocs size and surface, their surface structure and their impacts on the membrane fouling might be negligible. During preliminary operation of pilot-scale MBR system Gkotsis et al [54] reported that the low F/M ratio, low MLSS and high DO concentration increase the concentration of colloids in the mixed liquor which result in membrane fouling.

Regarding the F/M ratio, Banti et al [56] recommends operation of the MBR system at F/M ratio of 0.65 gCOD/gTSS.d and D.O concentration of 2.5 to obtain consistent performance in terms of effluent quality and membrane fouling and moderate concentration of filamentous bacteria. These values are similar to the range of F/M ratio and DO concentration of the current study. The presence of moderate concentration of filamentous bacteria in the MBR treating municipal wastewater improved the membrane fouling at TMP kept at 0.02 bar comparing to 0.14 bar in the control unit without filaments [56].

Table 6a: Statistical analyses between flux rates and TMP at similar HRT with different DO concentrations

Item	**HRT4 hrs**		**HRT6 hrs**		**HRT8 hrs**	
	High DO	Low DO	High DO	Low DO	High DO	Low DO
Flux rate, $L/m^2.h$	18.9±2.8a	18.7±2.4a	19.4±1.0a	19.2±2.5a	20.0±1.2a	19.7±1.3a
TMP, bar	0.118±0.088a	0.132±0.089a	0.108±0.068a	0.120±0.079a	0.094±0.047a	0.104±0.052a

Statistical analysis is carried out between each two columns within the same block and values with similar superscript letter are non-significant different

Table 6b: Statistical analyses between flux rates and TMP at high and low DO concentration

Item	High DO			Low DO		
	HRT 4 hrs	HRT 6 hrs	HRT 8 hrs	HRT 4 hrs	HRT 6 hrs	HRT 8 hrs
Flux rate, $L/m^2.h$	18.9±2.8a	19.4±1.0a	20.0±1.2b	18.7±2.4a	19.2±2.5ab	19.7±1.3b
TMP, bar	0.118±0.088a	0.108±0.068ab	0.094±0.047b	0.132±0.089a	0.120±0.079ab	0.104±0.052b

Statistical analysis is carried out between each three columns within the same block and values with similar superscript letter are non-significant different

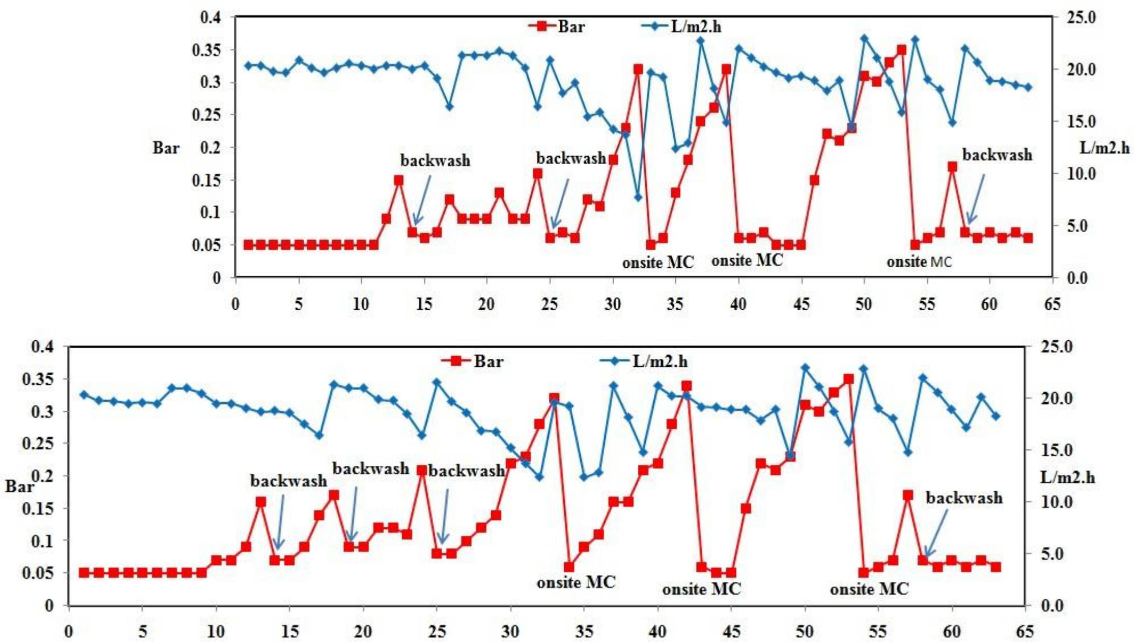
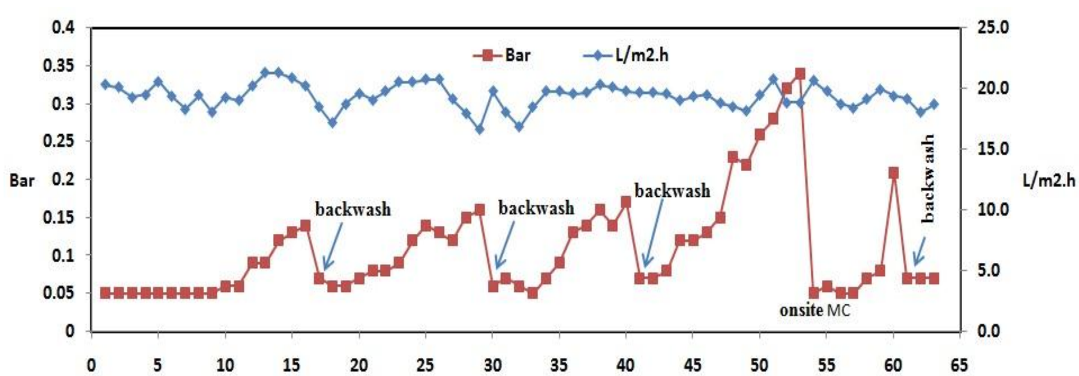


Figure 2a: TMP and permeate flux at 4 hrs HRT; high DO (top) and low DO (bottom)



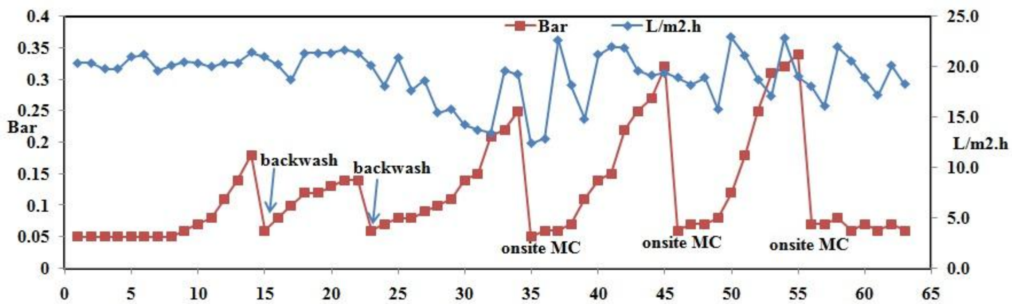


Figure 2b: TMP and permeate flux at 6 hrs HRT; high DO (top) and low DO (bottom)

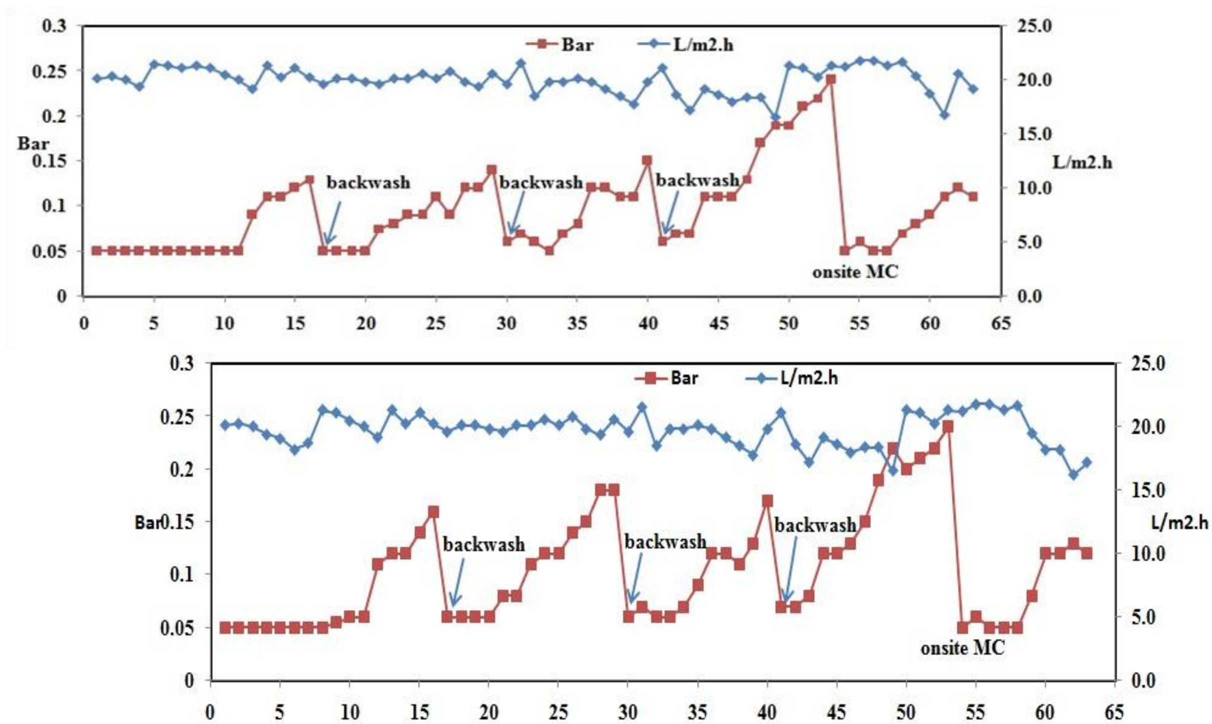


Figure 2c: TMP and permeate flux at 8 hrs HRT; high DO (top) and low DO (bottom)

4. Conclusions

- The cloth-media MBR showed significant impact of the DO concentration and HRT on the treatment performance with higher efficiency at high DO concentration and longer HRT.

- HRT was found more significantly affecting the TMP and permeate flow or flux rate at similar DO concentration. The TMP and flux rate in case of 6-hrs HRT have no significant differences with 4-hrs and 8-hrs. However, the TMP and flux rate at 8-hrs HRT were significantly better than the values at 4-hrs HRT.

- Both DO concentration and HRT have significant impact, directly or indirectly, on the membrane fouling. The high DO concentration at similar HRT non-significantly improves the sludge filterability or declines the membrane fouling; however, the frequency of backwashing and onsite mechanical cleaning was reduced at high DO concentration.

- Adjustment of operating conditions like F/M ratio, HRT and DO concentration plays a significant role in control of membrane fouling.

-Operation of the cloth-media submerged MBR system at F/M ratio of 0.65 gCOD/gTSS.d and DO concentration of 2.3 provide consistent performance in terms of effluent quality and membrane fouling.

- Economically, the system operation at low DO concentration (2 ppm) and medium HRT (6hrs) was found cost-effective, sustainable and provided treated effluent complying physico-chemically with reuse standards.

-Cloth-media MBR is sustainable for sewage under Egyptian conditions because it can be assembled using local materials and provides good quality effluent that is well nitrified, low in turbidity and organic carbon content and so easy to disinfect at low cost for agriculture reuse.

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6.References.

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أغشية حيوية منخفضة السعر لمعالجة مياه الصرف الصحي كمصدر غير تقليدي لمياه الري

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تعاني مصر من ندرة في مواردها المائية لذلك اصبحت الموارد غير التقليدية مطلب ضروري لتأمين الإحتياجات المائية المتزايدة في قطاعات التنمية المختلفة وخاصة الزراعة التي تستهلك حوالي 85% من موارد المياه العذبة. تمثل مياه الصرف المعالج بصورة جيدة مصدرا جيدا لري الأراضي والذي يمثل حلا بديلا للتخلص من الصرف المعالج في البيئة. في هذه الدراسة تم تصميم و تصنيع وتقييم أغشية حيوية تعتمد على الأقمشة كوسط ترشيح لمعالجة مياه الصرف الصحي عند ظروف تشغيل مختلفة. أغشية ترشيح قماشية بمساحة ترشيح 0,554 م^2 تم غمرها في حوض تهوية ،الحجم العملي النظري له 50 لتر بينما كان الحجم العملي المؤثر أو الفعلي هو 44,5 لتر. تم تشغيل الوحدة عند ثلاث فترات مكث مختلفة (4، 6 و 8 ساعات) وعند تركيز مرتفع للأكسجين الذائب (4,5 مجم/لتر) وأخر منخفض (2,3 مجم/لتر) و عمر حمأة 29,7 يوم وذلك بالتخلص من 1,5 لتر من المخلوط الممزوج (MLSS) يوميا. أوضحت نتائج تشغيل الوحدة تأثيرات محسوسة للأكسجين الذائب وفترات المكث على كفاءة المعالجة وذلك بالحصول على كفاءة أعلى عند الأكسجين الذائب الأعلى تركيز و فترة المكث الأطول. عند تركيز الأكسجين المرتفع كان مدى التركيزات المتبقية 10,4-20,3 مجم أحتياج أكسجيني كيميائي/لتر و 4,2-10,1 مجم أحتياج أكسجيني حيوي/لتر.عند تركيز الأكسجين المنخفض كان مدى القيم 17,5-30,1 و 7,6-14,8 مجم/لتر لكل من الأحتياج الكسجيني الكيميائي والحيوي على الترتيب. تبين من النتائج أن كل من الأكسجين الذائب وفترة المكث له تأثير محسوس بصورة مباشرة أو غير مباشرة على نفاذية الأغشية (Filterability) و إنسدادها (Membrane fouling). إقتصاديا وجد أن تشغيل الوحدة عند أكسجين ذائب منخفض (2 مجم/لتر) وفترة مكث متوسطة (6 ساعات) أجدى أقتصاديا، بشكل مستدام و يعطي مياه معالجة تتوافق فيزيقيا وكيميائيا مع معايير إعادة الإستخدام كما يمكن تطهيرها بتكلفة قليلة نظرا للشفافية العالية (انخفاض العكارة) وإنخفاض تركيز النشادر والكربون العضوي بها مما يمكننا من استخدامها الغير مشروط للزراعة.

الكلمات الدالة:

وسط قماشي، أغشية حيوية، موارد مياه غير تقليدية، إعادة استخدام المياه المعالجة، تراكم الحمأة والميكروبات على الأغشية.

Cloth-media, MBR, sewage, non-conventional water resource, effluent reuse, membrane fouling