Membrane microfiltration (MF) or ultrafiltration (UF) systems of activated sludge is crucial part of a bioreactor process used in municipal wastewater treatment. In this study, both cylindrical and flat sheet ceramic membranes were used to treat municipal wastewaters. The effects of removing water turbidity and coliform bacteria from an artificial wastewater were studied by performing batch experiments by MF and ultraviolet (UV) photolysis of 254 nm wavelength. It was shown that the microfiltration had a high effect of suspended solid removal. However, the effect of bacteria removal was limited so that the rate of cfu removal was approximately 61%. Combined consecutive processes in the treatment (MF/UV and UV/MF) confirmed that a specific porosity of the ceramic filter for bacteria removal was required. The continuous membrane bioreactor (MBR) tests performed by using a MF membrane with the pore size of 0.2 μm showed that particulate matter and microorganisms found in municipal wastewater could be effectively removed. Turbidity was decreased from 4.50 to 0.05 NTU, with a removal efficiency of greater than 98%. The permeate total suspended solid (TSS) content for the whole run was below 5 mgL\(^{-1}\). The density of total coliforms was decreased more than four orders of magnitude (from around \(1 \times 10^5\) mL\(^{-1}\) to less than 5 mL\(^{-1}\) in the effluent).

Keywords: Membrane bioreactors, combined processes, ceramic filters, UV photolysis, municipal wastewater.

Introduction

Currently, treated municipal wastewater is discharged to the environment and generally it is considered as a waste. However, municipal wastewater effluent should be regarded as a resource from which high quality water for reuse can be produced. An added benefit is that water reuse reduces the discharge of municipal wastewater to the environment and, thus, it offers a degree of source water protection.

In recent years, applications of membrane separation techniques in wastewater treatment have drawn worldwide attention to researchers and engineers. The membrane bioreactor (MBR) process, which consists of an activated sludge bioreactor and a microfiltration membrane, is an emerging biotreatment technology that has demonstrated a great promise in water reuse. It has the advantage of the rapid development in membrane manufacturing and the potential to fundamentally advance biological treatment processes. Possessing advantages such as excellent effluent quality, a high biomass concentration without any concern for sludge settling problems, a simple flow configuration and small footprint demand, MBRs have been successfully used in biological wastewater treatment and the reclamation of treated effluents\(^1\).

For the treatment of domestic wastewater, a sludge concentration from 3,000 to 10,000 mgL\(^{-1}\) or higher in mixed liquor suspended solid (MLSS) can be maintained in an MBR with a hydraulic retention time (HRT) of 10–20 h.\(^{12,3}\) This allows large macromolecules to be in contact with biomass for longer period than that within a conventional activated sludge process and therefore, this leads to achieve a chemical oxygen demand (COD) or a biological oxygen demand (BOD\(_5\)) removal of more than 98%. One particular element of interest is the MBR efficiency for the removal of pathogens in the treated water. The effect of disinfection can be reached by different methods. There are many approaches that are used for the disinfection of water. The advantages and disadvantages of each method are described in the literature.\(^4\) Production of disinfected water with constant high quality by use of membrane technology is a good alternative for the conventional treatment techniques, as the conventional methods of water treatment have their own
limitations in their ability of improved quality of water.\cite{5} The membranes are used in water purification, effluent polishing, virus removal, and ultrapure water production.

Municipal wastewaters typically contain pathogenic enteric bacteria, viruses, and intestinal parasites. Although primary and secondary wastewater treatment processes eliminate 90–99.9% of enteric microorganisms and tertiary treatment, such as filtration, may further reduce 90–99% of these microorganisms, purified wastewaters may still contain high microbial numbers.\cite{6} If a more efficient elimination of microorganisms is needed, a further disinfection must be performed on the wastewater. Chlorination is the traditional and most common wastewater disinfection method used worldwide. It is an efficient disinfectant against many enteric bacteria, but it has lower efficiency against bacterial spores and protozoan cysts.\cite{7} The use of chlorination has been decreasing, mainly due to toxic, mutagenic and/or carcinogenic disinfection by-products (DBPs) as well as the formation of chlorine residuals in the disinfection process.\cite{8,9}

Ultraviolet irradiation in the C-region (UV-C), with the wavelength of 254 nm or less, is also another important technique for water and wastewater disinfection. The number of plants using UV disinfection applications has been increasing in recent years. UV disinfection typically eliminates enteric bacteria, viruses, bacterial spores, and parasite cysts efficiently without producing DBPs or other chemical residues.\cite{10} The efficiency and reliability of UV disinfection greatly depend on the water quality, placing large demands on the upstream treatment processes.\cite{11} UV-C photolysis makes changes in the DNA of the microorganisms, which results in their death. Also, if UV is in the presence of hydrogen peroxide, plenty of hydroxyl radicals will be generated. Hydroxyl radicals, in turn, cause the degradation and destruction of organic matters.\cite{12–19}

This study examines the treatment of municipal wastewater using a membrane bioreactor (MBR) system. The MBR experiments were preceded by tests of comparative disinfection efficiencies of UV and microfiltration (MF) techniques. The effectiveness of microfiltration membranes incorporated in MBR was examined in terms of organic matter, nutrients, and microbial control. Single processes, such as UV photolysis, membrane processes, and biological processes, are not efficient and also not cost-effective due to their limitations in the treatment of wastewater as well their high operating and capital costs. It has been shown that combined processes, such as UV photolysis, chemical, or biological processes, is more efficient than single processes alone.\cite{20–24}

Materials and methods

**Experimental setup of the preliminary tests**

The preliminary tests were performed to compare MF and UV photolysis effects on removing water turbidity and coliform bacteria. The tests were performed using an artificial wastewater. The artificial wastewater was prepared by diluting 1 L of municipal wastewater collected from the Dubai Municipal Wastewater Treatment Site, Dubai, United Arab Emirates. The experiments of this section were performed in 9 L of deionized water. Four capsules of Polyseed (Bio-science, Inc.) containing a mixed culture of microorganisms were added to the water system along with 20 g/day bread and 20 g/day sugar as nutrient for one week. The wastewater characteristics after a two-day period of incubation contained 190 mgL\(^{-1}\) BOD\(_5\), 3.6 mgL\(^{-1}\) dissolved oxygen (DO), and 699 NTU turbidity. The pH of the system was 6.9. Throughout the incubation period, the system was aerated using an air diffuser. The treatment schemes performed in the preliminary tests were as follows:

(i) Scheme 1: UV treatment in batch conditions,
(ii) Scheme 2: Ceramic filtration in semi-batch mode,
(iii) Scheme 3: Ceramic filtration followed by UV treatment and,
(iv) Scheme 4: UV treatment followed by Ceramic filtration.

The experimental set up for the UV batch system along with the natural circulation and ceramic filtration systems for the preliminary tests is illustrated in Figure 1. The batch UV test was performed using a cylindrical reactor (80 × 450 mm) with effective volume of 2 L, in which the UV lamp (shell and tube type) with the maximum wavelength of 250 nm was immersed in the center of the photoreactor. The ceramic filter was a cylindrical microfilter with the diameter of 2.5 cm, surface area of 471.24 cm\(^2\), wall thickness of 0.65 cm, and the pore size of 0.8 μm. The ceramic filtration process was set up by connecting the filter to a vacuum pump. The process was carried out under vacuum pressure of 0.06 bar at almost constant flow rate varying within 31.2–31.7 cm\(^3\)s\(^{-1}\). The membrane permeability \(P\) was calculated as follows:

\[
P = \frac{\text{Flow Rate}}{\text{Pressure} \times \text{Membrane Area}} = \frac{31.7 \text{ cm}^3/\text{s} \times 3600 \text{ s}}{62.7 \text{ mmHg} \times (2 \times \pi \times 2.5 \times 30 \text{ cm}^2)}
\]

\[
= 3.86 \text{ cm}^3/\text{h.mmHg}
\]

To regenerate the ceramic filter, a backwash was applied. The backwash was performed by applying compressed air in the opposite direction of the water flow. The quality of raw and treated water was characterized by measuring BOD, pH, colony forming units (cfu), and the turbidity.

**Experimental setup of the laboratory scale MBR tests**

A submerged MBR, as shown in Figure 2, was used in the experimental study of this section. A ceramic flat sheet membrane module (ItN Nanovation GmbH, Germany), with a frame dimension \((L \times W)\) of 12×12 cm\(^2\), a pore size...
of 0.2 μm, and a total surface area of 0.048 m², was immersed inside an activated sludge bioreactor. The bioreactor was made of acrylic plate with dimensions \((L \times W \times H)\) of 15×3×30 cm³, and had an effective volume of 1 L with a water depth of 30 cm. A level controller was used to regulate the feeding pump, whilst the effluent was withdrawn directly from the MBR through the membrane by a suction pump. Therefore, the system was operating in a continuous mode. A manometer was mounted between the membrane module and the suction pump to monitor the trans-membrane pressure (TMP). The bioreactor was aerated intermittently to get cyclic aerobic and anaerobic conditions in the bioreactor to promote nitrification / denitrification and biological dephosphatation. The air was provided through an air diffuser at the bottom of the reactor to generate strong turbulence for membrane cleaning through the aerobic period. For the experiments using the flat sheet membrane, seed-activated sludge was collected from the Bourgas Sewage Treatment Works, Bourgas, Bulgaria, where the experiments of this section were performed, and placed in the MBR at an initial concentration of 1,235 mgL⁻¹ mixed liquor suspended solid (MLSS). During the stable operation, the membrane external fouling was also observed.

During the laboratory-scale MBR operation, the influent wastewater was a domestic sewage collected from the Bourgas Sewage Treatment Works, Bourgas, Bulgaria. The raw sewage had a BOD₅, COD, and ammonia nitrogen of approximately 150, 300, and 12 mgL⁻¹, respectively. Total suspended solids varied within 110-156 mgL⁻¹. The turbidity and total coliform density were about 4-5 NTU and 3.4 × 10⁵ mL⁻¹, respectively. The pH of the MBR influent varied from 6.5 to 7.3. The effluent suction pump was controlled by a timer based on a pre-determined time sequence of on/off switching to provide better membrane cleaning with the aeration and hence, to minimize the biofouling problem. The general MBR operation parameters during its stationary operation are summarised in Table 1.

All analyses were performed following Standard Methods. Turbidity was monitored by a turbidimeter (LP 2000, Hanna Instruments). Ammonia nitrogen was analyzed photometrically by nesslerization. The dissolved oxygen (DO) was determined by a DO probe (RE 347 Tx

### Table 1. Operational conditions of the submerged MBR in the laboratory-scale MBR tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation duration (d)</td>
<td>92</td>
</tr>
<tr>
<td>MLSS, (mgL⁻¹)</td>
<td>1235–4200</td>
</tr>
<tr>
<td>HRT (h)</td>
<td>1.98–1.66</td>
</tr>
<tr>
<td>Flux (mL·cm⁻²·h⁻¹)</td>
<td>70–220</td>
</tr>
<tr>
<td>Organic loading (gCOD·g⁻¹VSS·d⁻¹)</td>
<td>0.34–1.16</td>
</tr>
<tr>
<td>NH₃-N loading (g·g⁻¹VSS·d⁻¹)</td>
<td>0.016–0.054</td>
</tr>
<tr>
<td>pH</td>
<td>6.5–7.3</td>
</tr>
</tbody>
</table>
meter, EDT Instruments). Total coliform bacteria were enumerated by the membrane filtration method, with Gelman Sciences sterilized membrane and Paqua lab universal incubator as the nutrient medium.

### Results and Discussion

#### Preliminary Test Results

The decrease of turbidity and number of cfu (for the 45th and 65th min) through the processes of UV photolytic treatment and microfiltration are summarized in Table 2. The changes of cfu and turbidity during the whole period of UV treatment are illustrated in Figures 3 and 4, respectively. The colony number was decreased from the initial value of 17 to almost zero cfu in about 1 h by the UV photolysis alone (see Figure 3). In addition, the turbidity of the wastewater was decreased from 660 to 450 NTU after about 1 h using the UV photolysis alone (see Figure 4). The results of reduction in coli forming units through the consecutive ceramic filtration–UV treatment (Scheme 3) and the reverse processes of UV treatment–ceramic filtration (Scheme 4) are shown in Table 3.

![Colony counts versus time for the wastewater treatment using Scheme 1 (UV batch system only) in the preliminary tests. The colonies were counted in a 10-mL sample.](image)

The obtained results show that the MF with the ceramic filter (0.8 µm) is effective in removing the turbidity due to the suspended solids. According to the data presented in Table 2, its efficiency is around 71%. Evidently, considering the BOD₅ reduction (85%), the ceramic filter removes most of the suspended organic matter. However, the UV treatment on the turbidity was less effective, 29–32%, which is due to the lowering of the biological activity in the treated water. Concerning the colony counting results, obviously the effect of UV treatment is a time-dependent process. Figure 3 shows that cfu number approaches zero at UV treatment time over 60 min. In spite of the notable effect of microfiltration for suspended solids removal, the effect of bacteria removal (~61%) is hardly acceptable. The combined (MF/UV and UV/MF) and the stand-alone MF treatment processes confirm that specific porosity of the ceramic filter for bacteria removal is required. Based on these preliminary tests, a flat sheet MF membrane with lower porosity was used for further experiments.

#### Laboratory-scale MBR Results

The submerged MBR for the treatment of the contaminated wastewater was continuously operated for more than

### Table 2. Quality of wastewater before and after treatment by UV photolysis and cylindrical ceramic filter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Raw wastewater</th>
<th>UV treatment (Scheme 1)</th>
<th>Ceramic filtration (Scheme 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity (NTU)</td>
<td>659</td>
<td>473</td>
<td>189</td>
</tr>
<tr>
<td>Colony forming units/10 mL</td>
<td>18</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>BOD₅ (mgO₂·L⁻¹)</td>
<td>190</td>
<td>—</td>
<td>180</td>
</tr>
</tbody>
</table>

Fig. 3. Colony counts versus time for the wastewater treatment using Scheme 1 (UV batch system only) in the preliminary tests. The colonies were counted in a 10-mL sample.
Ceramic microfiltration

90 days at different conditions. During its steady state operation, the MBR influent had an average COD and NH\textsubscript{3}-N concentrations of 300 and 14 mgL\textsuperscript{-1}, respectively. The organic content was monitored by COD measurements. The first run was conducted at continuous aeration. The obtained results through the first run in 27 days, as shown in Figure 5, show that 78 to 92% of the organics were removed by the MBR treatment, thus reducing the COD to an average of 40 mgL\textsuperscript{-1} in the effluent. The applied hydraulic retention time (HRT) during this period of study was 3.2–8.1 h. The observed gradual increase of HRT was due to the membrane fouling, which decreases membrane permeability. The results show evidently that the COD removal rates are not influenced by the HRT applied. Comparatively, the lower rates of organic matter removal were recorded to be 78% at the lowest influent COD concentration, namely at influent COD concentration of 135 mgL\textsuperscript{-1}. During this run, the ammonia nitrogen influent and effluent concentrations were observed as depicted in Figure 5. Despite the fluctuation of NH\textsubscript{3}-N concentration in the MBR influent, the NH\textsubscript{3}-N concentration was usually below 0.1 mgL\textsuperscript{-1} in the effluent. Such high effect of nitrification was observed in another MBR study.\textsuperscript{[27]} The obtained results in this study may be attributed to the high solid retention time (SRT) allowing greater accumulation of nitrifying bacteria in the reactor, thus performing nitrification at a faster rate.

Combined effects of organic carbon assimilation, nitrification, and bio-dephosphatation

The second set of experiments were conducted in conditions of sequential change (every two hours) of DO concentration in the bioreactor. Every two hours, the air supply was terminated. A typical daily change of dissolved oxygen concentration (DO) is depicted in Figure 6. Similar to Run 1, the process was studied at different HRT. Within this run, the HRT applied was in the range of 1.98–11.66 h.

![Fig. 4. Turbidity versus time for the wastewater treatment using Scheme 1 (UV batch system only) in the preliminary tests.](image)

![Fig. 5. Quality of wastewater before and after treatment using flat sheet ceramic membrane for the laboratory scale membrane bioreactor system. The effluent NH\textsubscript{3}-N after 2 days was below 0.1 mgL\textsuperscript{-1}. C is the concentration in terms of mgL\textsuperscript{-1}.](image)

Table 3. Colony count results for Scheme 3 (ceramic filtration semi-batch followed by UV treatment) and Scheme 4 (UV batch followed by ceramic filtration) in the preliminary tests

<table>
<thead>
<tr>
<th>Integrated Processes</th>
<th>Time of UV treatment (min)</th>
<th>cfu/10 mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme 3*</td>
<td>19.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>34.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>49.5</td>
<td>0</td>
</tr>
<tr>
<td>Scheme 4**</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>2</td>
</tr>
</tbody>
</table>

*The cfu values for the ceramic filter influent and effluent were 18 cfu/10 mL and 9 cfu/10 mL, respectively.

**The cfu value for the UV reactor influent was 17 cfu/10 mL.
The effects of continuous membrane fouling resulted in an increase of HRT applied. The obtained results show that during the entire period of the run, the efficiency related to the COD removal was above 84%. The highest recorded rate of COD removal was 90%. It was confirmed that the changes of HRT do not have influence on COD removal. During the second run, the effect of nitrogen removal was also monitored. As Figure 7 shows, ammonia was oxidized to a high extent so that its effluent concentration was lower than 0.1 mgL$^{-1}$. Nitrogen in different forms was balanced reasonably well with most of the ammonia being converted to nitrate and subsequently denitrified to free nitrogen (81–83%). The residual nitrite was always lower than 200 $\mu$gL$^{-1}$. Nitrite accumulation, which may occur in the biofiltration process, was not observed in the MBR treatment. The monitoring of effluent phosphorous content also showed an unexpected high effect of its removal. A stable effect of phosphorous removal, above 94%, was recorded, as depicted in Figure 8.

The sludge concentration in the MBR was increased from around 1,235 to 4,200 mgL$^{-1}$ in MLSS, while the ratio of volatile suspended solid to suspended solid (VSS/SS) was nearly constant at 0.90. Following the bio-flocculation processes in MBR and membrane separation, particulate matter and microorganisms were effectively removed from the effluent. Turbidity was decreased from 4.50 to 0.05 NTU, with removal efficiency of greater than 98%. The permeate total suspended solid (TSS) content for the whole run was below 5 mgL$^{-1}$. The density of total coliforms was decreased more than four orders of magnitude from around $1 \times 10^5$ mL$^{-1}$ to less than 5 mL$^{-1}$ in the effluent. The experimental results suggest that the MBR process can be both technically and economically feasible for water reuse.

Conclusions

Both cylindrical and flat sheet ceramic membranes were effective in obtaining high quality water from municipal wastewater. This can help in the scarce resources of water by water reuse which will reduce the discharge of municipal wastewater to the environment and thus, offers a degree of source water protection. The batch comparative studies of MF and UV effects on removing wastewater turbidity and coliform bacteria from an artificial wastewater showed a high effect of microfiltration for suspended solids removal. It was shown that the effect of bacteria removal was limited (the rate of $cfu$ removal was around 61%) in utilizing MF membranes with pore size of 0.8 $\mu$m. The combined treatment processes (MF/UV and UV/MF) confirm that specific porosity of the ceramic filter for bacteria removal was required. The continuous MBR tests performed with flat ceramic MF membrane with pore size of 0.2 $\mu$m showed that particulate matter and microorganisms of municipal wastewater could be effectively removed. Specifically, the removal efficiency with respect to turbidity was greater than 98%, while the density of total coliforms was decreased more than 4 orders of magnitude, from around $1 \times 10^5$ mL$^{-1}$ to less than 5 mL$^{-1}$ in the effluent.
Ceramic microfiltration

References


