Microbiological and physicochemical evaluation of the effluent quality in a membrane bioreactor system to meet the legislative limits for wastewater reuse

Konstantinos Azis, Charalampos Vardalachakis, Spyridon Ntougias and Paraschos Melidis

ABSTRACT

The aim of this study was to assess the efficacy and effluent quality of a pilot-scale intermittently aerated and fed, externally submerged membrane bioreactor (MBRes) treating municipal wastewater. The effluent quality of the MBRes was evaluated regarding system ability to comply with the Greek legislative limits for restricted and unrestricted wastewater reuse. The average permeate flux was 13.9 L m⁻² h⁻¹, while the transmembrane pressure remained above the level of ~110 mbar. Experimental data showed that biochemical oxygen demand, chemical oxygen demand, total nitrogen, PO₄³⁻ - P and total suspended solids removal efficiencies were 97.8, 93.1, 89.6, 93.2 and 100%, respectively, whereas turbidity was reduced by 94.1%. Total coliforms and Escherichia coli were fully eliminated by ultrafiltration and disinfection methods, such as chlorination and ultraviolet radiation. In agreement with the Greek legislation (Joint Ministerial Decree 145116/11) and the guidelines recommended for the Mediterranean countries, the disinfected effluent of the MBRes system can be safely reused directly for urban purposes.

INTRODUCTION

The Southern European countries are called to confront issues regarding water scarcity and water supply irregularities, particularly during the summer period. Wastewater reclamation and water reuse present a favorable solution to the growing pressure on water resources, as a result of anthropogenic activities (Aggelakis et al. 1999; Aggelakis & Bontoux 2001; Bixo et al. 2006, 2008). Nevertheless, the poor microbiological quality of the reclaimed wastewater increases health risks since coliforms are present in high densities. Innovative wastewater treatment technologies, such as ultrafiltration, can minimize environmental health risks and improve effluent quality (Salgot et al. 2006; Mara et al. 2007; Arévalo et al. 2009). Biological nutrient removal (BNR) can be achieved by automatically controlled aeration through the establishment of alternating anoxic–aerobic periods in the same bioreactor without spatial phases separation (Battistoni et al. 2004; Melidis et al. 2014). The on/off air supply control provides a high degree of operational flexibility and minimizes the operating costs. In addition, intermittent feeding results in periodic substrate saturation of the BNR systems (Aulenta et al. 2003; Kantartzis et al. 2010). The feeding within a short period of time, at the beginning of the anoxic phase, provides adequate easily biodegradable organic matter that increases denitrification efficiency (Melidis 2014). Indeed, improved effluent quality is required to meet the strict legislative limits for agricultural or landscape irrigation, urban and suburban uses, industrial reuse and enrichment of aquifers. In Greece, the Joint Ministerial Decree (JMD) 145116/11 defines the physicochemical and microbiological requirements regarding wastewater reuse. According to the JMD 145116/11, certain parameters have to be monitored during wastewater reuse applications, like nutrients and suspended solids (SS) concentrations. Moreover, reduction of total coliforms (TC) and Escherichia coli (E. coli) counts is of great importance since waterborne pathogens can cause several public health problems (Rose et al. 1996; Costan-
Longares et al. 2008). Therefore, microbial load should be reduced from the reclaimed water before discharging. Membrane filtration is essential for the reclamation of a permeate of improved microbiological quality, suitable for reuse purposes (Xing et al. 2000; Melin et al. 2006; Marti et al. 2011; Malamis et al. 2015), even though complete removal of pathogens cannot be expected, since growth of microorganisms can occur in water distribution system facilities or during storage. In addition, disinfection with chlorination or ultraviolet (UV) radiation can further improve the microbiological quality of the effluent in membrane bioreactor (MBR) systems, legislatively required for several water reuse applications (Ottoson et al. 2006; Arévalo et al. 2009). UV radiation penetrates the microbial cell wall, disrupting thus the cells’ genetic material and stopping reproduction (Lehr & Keeley 2005), whereas chlorine can damage cell membranes, inhibiting respiratory chain activity, glucose transport and protein synthesis (LeChervallier & Kwok-Keung 2004). Therefore, the purpose of this research work was to examine the ability of an ultrafiltration, externally submerged membrane bioreactor (MBRes) system in retaining microbial pathogens and to investigate the disinfection effectiveness of sodium hypochlorite (NaOCl) and UV radiation in order to meet the wastewater reuse legislative limits needed for unrestricted irrigation, urban and suburban uses and enrichment of aquifers.

METHODS

Operating conditions of the MBRes system

The MBR system consisted of an equalization tank (20 L), the main bioreactor (120 L) and the external membrane tank (80 L). The intermittently aerated and fed MBRes system was operated under a sewage flow rate of 61.2 L d⁻¹ (3.825 L per cycle). The aeration and the externally submerged membrane tanks were equipped with air-compressors. The aeration in the membrane tank (6.17 L min⁻¹) was provided only during the permeate pumping period (the last 15 min of the aeration phase) in order to clean the membrane and improve filterability (Kang et al. 2003; Nywening & Zhou 2009), removing large biosolids attached to the membrane surface and preventing ‘reversible’ fouling. The dissolved oxygen (DO) concentration, which was measured by a DO probe, was within the range of 3–4 mg L⁻¹ in the main reactor throughout the entire aerobic phase, ensuring adequate oxygen to achieve complete biological oxidation processes. This was achieved by an air-compressor, providing 1.5 L min⁻¹ of air. The activated sludge was re-circulated between the main bioreactor and the membrane tank through the use of an internal recirculation pump, which had a frequency response of 3 min and a recirculation rate of 280 L h⁻¹. The high recirculation rate ensured complete equalization of the mixed liquor SS in both tanks. No sludge settling occurred in the membrane tank. Mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) concentrations increased from 2.2 and 1.9 g L⁻¹ to 5.7 and 5.4 g L⁻¹, respectively, with a mean value of 4.1 and 3.6 g L⁻¹, respectively, whereas the respective F/M ratio decreased from 0.72 to 0.12 BOD g⁻¹ VSS d⁻¹ (BOD: biochemical oxygen demand; VSS: volatile suspended solids), showing a mean value of 0.26 g BOD g⁻¹ VSS d⁻¹. No sludge was wasted. A schematic layout of the system is provided in Figure 1. The BNR processes and the transmembrane pressure (TMP) were automatically controlled by a programmable logic controller (PLC). In particular, the PLC controlled each operation cycle by switching on/off the air supply, resulting in a fixed aerobic period of 1 h and a respective anoxic phase of 30 min. This indicates alternating oxic/anoxic cycles of 1 h/0.5 h (16 cycles per day) in order to achieve effective nitrification/denitrification. A typical ammonia oxidation (nitrate formation) and nitrate reduction cycle is illustrated in Figure 2, indicating an effective operating MBR system. Moreover, the controller also regulated the peristaltic pumps, the mixer and the mechanical parts of the membrane module. The membrane operation encompassed a backwash and a fine bubble aeration period (specific aeration capacity of 0.8 m³ m⁻² h⁻¹, absolute value of 4.5 L min⁻¹). Three successive filtration cycles were started during the last 15 min of the aerobic period, each one comprising the permeate phase (480 sec), the first relax phase (50 sec), the backwash (60 sec) and the second relax phase (50 sec) (Vardalachakis et al. 2016).

The influent wastewater was added in each operating cycle at the beginning of the anoxic phase within a time period of 3 min in order to facilitate the denitrification process. The duration of nitrification phase (1 h) was sufficient to achieve complete ammonia oxidation.

Membrane characteristics

A semipermeable flat sheet membrane (Microdyn Nadir UP-150) served as a selective barrier for the retention of microorganisms from the effluent (Table 1). The membrane comprised hydrophilic polyether-sulfone sheets, which had a thickness of 2 mm, pore size of 0.04 μm (cut-off,
150 kDa) and a total active surface of 0.34 m². Membrane cleaning was achieved by either automated maintenance cleaning (backwash) or intensive cleaning (chemical bath) using NaOCl concentration of 100 ppm. The membrane could operate under a pH range of 2–10, resisting a maximum filtration pressure of −400 mbar and a maximum operating backwash pressure of +150 mbar. The manufacturing clean water flux and the specific aeration capacity were 15 L m⁻² h⁻¹ and 0.8 m³ m⁻² h⁻¹, respectively.

**Disinfection equipment and methods**

A cylindrical closed-type system (PurePro, drinking water system) was used for applying UV radiation. UV was applied in the effluent of the MBRes unit, whereas the maximum pressure resistance of the unit was 5.86 bar. The characteristics of the UV purifier were: radius, 2.5 cm; height, 50 cm; activate surface, 292.5 cm²; capacity, 464.5 mL; germicidal quartz lamp, 12 W; microbicide wavelength, 254 nm; flow rate, 128 mL min⁻¹; flux 7.52 L m⁻² h⁻¹; exposure time, 222 s; and energy dose, 4.5 J cm⁻². The applied dose was calculated according to US EPA (1999).

In the chlorination method, the NaOCl dose for complete TC elimination was calculated by the Tchobanoglous et al. (1998) equation. NaOCl was applied in the effluent at a dose of 0.5 mg L⁻¹. The minimum retention time of NaOCl solution for disinfection was estimated to be 1 h. TC and *E. coli* were enumerated in the effluent of MBRes in the absence and presence of the disinfection methods applied.

**Wastewater characteristics**

The MBRes system was operated with domestic wastewater from the University Campus of Xanthi. The influent sewage characteristics were: BOD₅, 149 ± 37.2 mg L⁻¹; total chemical oxygen demand (COD), 388 ± 196 mg L⁻¹; SS, 201 ± 88.5 mg L⁻¹; total Kjeldahl nitrogen (TKN),
73.8 ± 12.9 mg L⁻¹; NH₄⁺-N, 57.3 ± 15.8 mg L⁻¹; electrical conductivity (EC), 1,229 ± 170 μS cm⁻¹; and pH, 7.31 ± 0.23. TC and E. coli were counted as 9.4 ± 5.7 (×10⁶) and 64 ± 40 (×10⁴) cfu/100 mL, respectively.

**Analytical methods**

Samples were obtained from the influent and the effluent of the MBRes unit for the measurement of the microbiological and physicochemical parameters. NO₃⁻-N and NH₄⁺-N concentrations were determined by ion chromatography (Dionex IC3000) and the steam distillation method (Clesceri et al. 1998), respectively. COD, BOD₅, TKN, SS, MLSS and MLVSS concentrations were measured according to the standard methods (Clesceri et al. 1998). EC and pH were determined through the use of a Crison CM35 and a Metrohm 632 pH meter, respectively. DO concentration was measured by an oxygen meter (WTW Handheld meter Oxi340i). TC and E. coli counts were estimated by filtering 100 mL of sample through a 0.45 μm pore-size membrane, placing the filters on m-Endo and Chromocult coliform agar plates and incubating the cultures for 22–24 h at 35 ± 0.5 °C and 44 ± 0.5 °C, respectively. Turbidity was determined by using the Hach 2100Q turbidity meter. Membrane cleaning was achieved by either automated maintenance cleaning (backwash) or intensive cleaning (chemical bath) using NaOCl concentration of 100 ppm.

**RESULTS AND DISCUSSION**

A detailed description of the MBRes system performance is presented in Table 2. Effluent EC and pH were equal to 1,140 ± 98 μS cm⁻¹ and 7.08 ± 0.27, respectively. PO₄³⁻-P was effectively removed from the system (93.5% removal efficiency), resulting in PO₄³⁻-P concentration of 0.21 mg L⁻¹ in

![Figure 2](image_url) Typical ammonia oxidation (nitrate formation) and nitrate reduction cycle.
the permeate, a value that not only complies with EU legislation, but is also much lower than the legislative limits. MLSS and MLVSS concentrations were 4.38 ± 1.26 g L⁻¹ and 3.87 ± 1.31 g L⁻¹ during system operation. Permeate flux was equal to 13.9 L m⁻² h⁻¹. The permeability was 85.2 ± 3.5 L m⁻² h⁻¹ bar⁻¹ and the respective resistance was 7.21 ± 2.78 m⁻¹. TMP was equal to 142 ± 51.6 mbar. In the case of total SS, the limits specified by the Greek legislation for wastewater reuse are ≤10 mg L⁻¹ for restricted and unrestricted irrigation and ≤2 mg L⁻¹ for urban use (in 80% of the samples analyzed). As expected, ultrafiltration with a pore size of 0.04 μm retained 100% of the SS, complying with the effluent quality limits for unrestricted use (≤2 mg L⁻¹). Based on turbidity measurements, effluent NTU (Nephelometric turbidity units) values varied between 1.2 and 3.6 and the mean value (± SE) was equal to 2.7 ± 0.7. In particular, turbidity expressed as NTU was near the limit threshold set for unrestricted use, but lower than values reported in several analogous studies, where NTU values between 5 and 10 were determined (Xing et al. 2000; Jefferson et al. 2001).

### Organic carbon removal

According to the JMD 145116/11 for wastewater reuse, BOD₅ is the main quality parameter regarding the organic carbon content of the treated effluent. The effluent BOD₅ value permitted by the law is ≤25 mg L⁻¹ for restricted irrigation and ≤10 mg L⁻¹ in 80% of all samples analyzed, for unrestricted use (urban and suburban green uses, groundwater recharge). The MBRes system resulted in low effluent BOD₅ concentrations, varying between 1 and 6 mg L⁻¹ (Figure 3). In all cases, the mean value (± SE) of BOD₅ was estimated as 3.4 ± 1.4 mg L⁻¹, meeting the legislative limits for unrestricted irrigation and suburban use (Malamis et al. 2015). Similar BOD₅ concentrations in the permeate of two MBR systems

<table>
<thead>
<tr>
<th>Biological processes performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>pH in</td>
</tr>
<tr>
<td>pH out</td>
</tr>
<tr>
<td>EC_in (μS cm⁻¹)</td>
</tr>
<tr>
<td>EC_out (μS cm⁻¹)</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
</tr>
<tr>
<td>BOD_in (mg L⁻¹)</td>
</tr>
<tr>
<td>BOD_out (mg L⁻¹)</td>
</tr>
<tr>
<td>COD_in (mg L⁻¹)</td>
</tr>
<tr>
<td>COD_out (mg L⁻¹)</td>
</tr>
<tr>
<td>TKN_in (mg L⁻¹)</td>
</tr>
<tr>
<td>TKN_out (mg L⁻¹)</td>
</tr>
<tr>
<td>NH₄-N_in (mg L⁻¹)</td>
</tr>
<tr>
<td>NH₄-N_out (mg L⁻¹)</td>
</tr>
<tr>
<td>NO₃-N_out (mg L⁻¹)</td>
</tr>
<tr>
<td>PO₄-P_in (mg L⁻¹)</td>
</tr>
<tr>
<td>PO₄-P_out (mg L⁻¹)</td>
</tr>
</tbody>
</table>

Figure 3 | Influent and effluent BOD₅ concentrations and removal efficiencies.
using ultrafiltration membranes were reported by Melin et al. (2006) and Arévalo et al. (2012). Regarding COD, the effluent concentration was equal to $20.7 \pm 12 \text{ mg L}^{-1}$, corresponding to a COD efficacy of 93.1%. These results were in accordance to the findings of Melin et al. (2006), who reported a COD removal efficiency of 89–98%, with effluent COD varying between 10 and 30 mg L$^{-1}$. Moreover, effluent COD concentrations of 25–35 mg L$^{-1}$ were determined by Pinnekamp & Friedrich (2013) during the study of three ultrafiltration MBR systems in Germany.

Nitrogen removal

MBRs led to high nitrogen removal efficiency, with effluent total nitrogen (TN) being lower than 10 mg L$^{-1}$, which is the limit set by the EU legislation for population equivalent greater than $10^5$. In particular, effluent ammonium nitrogen concentration was $2.41 \pm 0.36 \text{ mg L}^{-1}$, resulting in a mean removal efficiency of 95.7% (Figure 4). Complete denitrification was achieved since a negligible amount of nitrates ($0.48 \pm 0.52 \text{ mg L}^{-1}$) was detected in the filtrate and effective ammonia oxidation occurred. The average TKN removal efficiency was estimated as 90.5% and the effluent concentration was $6.76 \pm 1.39 \text{ mg L}^{-1}$. The corresponding TN value was $7.24 \pm 1.43 \text{ mg L}^{-1}$. A similar effluent TN value ($7.8 \text{ mg L}^{-1}$) was determined by Kim et al. (2005) during operation of an MBR under alternating anoxic-aerobic conditions. Likewise, similar effluent TKN concentration was recorded by Monclús et al. (2010) using a microfiltration MBR unit. Therefore, the legislative requirements were met for unrestricted irrigation regarding industrial use, urban and suburban green applications, and groundwater recharge.

Microbiological effluent quality

In general, bacterial cells have diameter 0.6–1.2 μm and length 2–3 μm (Zhang & Farahbakhsh 2007). Based on the ultrafiltration membrane pore size (0.04 μm), it can be assumed that this type of membrane should provide complete bacterial removal and the permeate should be free of TC and $E. coli$. Indeed, waterborne pathogens reduction in MBR systems can be achieved by size exclusion (due to the pore size) and by sorption to membrane surface and/or cake layer (Le-Clech et al. 2006; Marti et al. 2011). This goal was achieved for the $E. coli$ since the latter was not detected during the whole experimental period (0–1 cfu/100 mL). The absence of an $E. coli$ population complies with the effluent quality standards of the Greek legislation (set limits ≤200 cfu/100 mL for restricted irrigation and ≤5 and ≤50 cfu/100 mL in 80% and 95%, respectively, of the samples analyzed for unrestricted irrigation). In agreement, Arévalo et al. (2012) showed $E. coli$ effluent concentrations of 0.2 cfu/100 mL. In a full-scale MBR plant, Battistoni et al. (2006) also reported a low $E. coli$ effluent concentration of 3.8 and 2.4 cfu/100 mL during the autumn and the summer period, respectively. According to the Greek legislation, TC enumeration is required for urban wastewater reuse. For urban and suburban green applications and groundwater recharge, the TC limits are 2 cfu/100 mL and 20 cfu/100 mL in 80% and 95%, respectively.
respectively, of the samples analyzed. However, TC was measured in high concentrations during the first experimental period, where no disinfection methods were applied (Table 3). To solve this problem, systematic cleaning of the effluent pipes with NaOCl was implemented, resulting in complete elimination of TC counts (Table 3), indicating a source of external contamination. It appears that the stagnant water in the pipes led to the growth of TC. This was strengthened by the facts that E. coli was totally retained by the membrane and no fecal contamination could occur in the pipes. As an additional strategy to secure microbiological quality, densification methods, i.e. chlorination and UV radiation, were applied. As expected, chlorination of the permeate resulted in 100% TC reduction, with the effluent meeting the legislative limits for urban use. UV radiation after ultrafiltration also led to complete inactivation (Table 3). Therefore, both chlorination and UV radiation improved microbiological effluent quality, meeting the legislative limits of ≤2 and ≤20 cfu 100 mL⁻¹ in 80% and 95%, respectively, of the samples analyzed needed for urban use.

### CONCLUSIONS

An MBRes plant was examined in order to assess the potential of reusing the permeate obtained. The MBRes system resulted in BOD₅, COD, TN and PO₄³⁻P removal efficiencies of 97.8, 93.1, 89.6 and 93.2%, respectively. Moreover, the ultrafiltration MB unit highly reduced turbidity and TSS concentration, by 94.1% and 100% respectively. In comparison to the Greek legislation for wastewater reuse (JMD 145116/2011), a low effluent BOD₅ concentration (3.4 ± 1.4 mg L⁻¹) was achieved, which met the legislative limits for unrestricted irrigation and urban use. The effluent TN (<15 mg L⁻¹) and ammonia nitrogen concentrations (about 2 mg L⁻¹) met the legislative limits for unrestricted irrigation, industrial use, urban and suburban green applications, and groundwater recharge. The SS concentration and permeate NTU values complied with the required limits for unrestricted use (although marginally for turbidity). Total retention of E. coli was achieved by the ultrafiltration membrane, while cleaning of the effluent pipes should be periodically performed to avoid external contamination and the growth of coliforms, due to the stagnant water remaining in the pipes. On the other hand, disinfection methods, i.e. chlorination and UV radiation, guarantee complete elimination of TC and E. coli, improving microbiological effluent quality and preventing public health risks. In conclusion, ultrafiltration MB systems can provide an improved effluent quality, which complies with the legislative limits for restricted and unrestricted irrigation and various urban and suburban uses.

### ACKNOWLEDGEMENTS

This paper was presented in the 2nd EWaS International Conference ‘Efficient & Sustainable Water Systems Management toward Worth Living Development’, 1–4 June, Chania, Crete, Greece.

---

**Table 3** | Microbiological effluent quality of an ultrafiltration MBRes treating municipal wastewater

<table>
<thead>
<tr>
<th>Measurement</th>
<th>TC (cfu/100 mL)</th>
<th>E. coli (cfu/100 mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrafiltration only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1,600</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>4,300</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1,800</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>10,800</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>11,600</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>6,100</td>
<td>0</td>
</tr>
<tr>
<td>Ultrafiltration + external pipe cleaning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ultrafiltration + NaOCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>119</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ultrafiltration + UV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
REFERENCES


Malamis, S., Andreadakis, A., Mamais, D. & Noutsopoulos, C. 2015 Can strict water reuse standards be the drive for the wider implementation of MBR technology? Desalination and Water Treatment 53 (12), 3303–3308.


Pinnekamp, J. & Friedrich, H. 2015 Membrane Technology for Wastewater Treatment. FIW Verlag, Aachen, Germany.
Removal of pathogenic and indicator microorganisms by a
full-scale water reclamation facility. Water Research 30 (11),
2785–2797.
Wastewater reuse and risk: definition of key objectives.
Tchobanoglous, G., Darby, J., McArdle, J., Genest, P. & Tylla, M.
1998 Ultrafiltration as an advanced tertiary treatment
process for municipal wastewater. Desalination 119 (1–3),
315–322.
US EPA 1999 Alternative Disinfectants and Oxidants Guidance
Manual, EPA 815-R-99-014. United States Environmental
Protection Agency, USA.
Vardalachakis, Ch., Azis, K., Ntougias, S. & Melidis, P. 2016
Evaluation of an esMBR system efficiency to meet the
wastewater reuse legislation limits. In: Efficient &
Sustainable Water Systems Management Toward Worth
Living Development (V. Kanakoudis, G. Karatzas &
E. Keramaris, eds), 2nd EWaS International Conference,
1–4 June, Chania, Crete, Greece.
Xing, C.-H., Tardieu, E., Qian, Y. & Wen, X.-H. 2000
Ultrafiltration membrane bioreactor for urban wastewater
and coliform bacteria from municipal wastewater by various
wastewater treatment processes: implications to water reuse.
Water Research 41 (12), 2816–2824.

First received 9 January 2017; accepted in revised form 5 June 2017. Available online 19 June 2017