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Promoting on-site urban wastewater reuse through MBR–RO treatment

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ABSTRACT

A compact membrane bioreactor and reverse osmosis (MBR–RO) system was installed and set in operation in KEREFYT, EYDAP, in order to assess the potential reuse applications of the reclaimed water. Practicing the sewer mining (SM) approach, the feed of the unit was directly drained from the sewage network. Monitoring of system's performance was performed through a series of lab analyses and online measurements. According to the results, it is concluded that both MBR and RO effluent present very high quality characteristics. The RO effluent's quality in terms of organic content (0.9 mg/L BOD_5 and not detectable total suspended solids), ammonium nitrogen (0.25 mg/L), turbidity (0.32 NTU), *Escherichia coli* (not detectable) and total coliforms (not detectable) could fully meet the water quality requirements for reclaimed water, as dictated by the Greek legislation. Furthermore, the application of SM practice through the implementation of an on-site compact treatment system consisting of a pretreatment unit followed by an MBR and a UV disinfection unit can reliably meet all the national and international criteria set for all types of non-potable wastewater reuse at a rather moderate cost. The addition of an RO unit is fully justified in the case of saline wastewater and/or in cases where strict limit values for heavy metals and micropollutants in the reclaimed water have been set.

Keywords: Sewer mining; Water reuse; Wastewater reclamation; Membrane bioreactor; Reverse osmosis; Emerging contaminants

1. Introduction

Due to global climate change and rapid population growth, there has been a worldwide effort to reduce water demand. Substitution of freshwater for non-potable uses with water from alternative sources, such as rainwater or treated blackwater and greywater, is being encouraged so as to reduce freshwater demand. Latest wastewater recycling invention called sewer mining (SM) is gradually increasing in popularity due to its high treatment efficiency as well as the fact that less space is required to install the treatment unit. This practice belongs to the broader group of decentralized options for water recycle/reuse [1]. SM does not use conventional wastewater treatment configurations, but alternative ones that enable the usage of compact, portable and advanced treatment units. Moreover, direct SM can reduce the need for additional infrastructure and ongoing energy consumption to transmit wastewater to a centralized treatment facility and then recycled water to the point of use [2].

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An innovative small footprint SM packaged treatment unit for urban reuse has been placed in KEREFYT, EYDAP, in the Metamorfosi region (Athens, Greece). Athens demo site tests the idea of SM as a concept for distributed reuse within the urban environment, exploiting state-of-the-art information and communication technology solutions for distributed monitoring and management. Reused water characteristics and their impacts on soil are also being tested, via on-site irrigation of urban green. Finally, the demo site is examining a major component of ecosystem services specifically relevant for arid regions: the mitigation of heat island effects due to irrigation of urban green. This is performed through sprinkler irrigation – with the unit's reclaimed water – on a grass field, located near the unit.

The main advantages of the SM unit installed in the Athens demo site are:

- Production of high quality recycled water due to the combination of membrane bioreactor (MBR) with reverse osmosis (RO), conforming to stringent performance criteria, including health and water quality standards.
- Minimum landscape disruption due to the small size of the unit coupled with the lack of odors and noise pollution, making it suitable for installation in the urban environment. Adding to that, computational simulations can identify optimal installation spots, e.g., selection of placement areas for minimization of hydrogen sulfide build-up in sewer pipes [3].
- Fully independent function of the system provided by the installed automations, as well as the online monitoring system that ensures a high quality of the treated water stream.
- Ability of direct mining of sewage from the network, close to the point-of-use, with minimum infrastructure required and low transportation costs for the treated effluent.
- In view of the above, the objective of this study was to assess the performance of an MBR–RO pilot system, and to explore the feasibility of reclamation and reuse of the treated effluent for urban use.

2. Materials and methods

2.1. Description of the MBR–RO pilot system

A dual-membrane process, such as an ultrafiltration (UF) and RO, is becoming increasingly attractive owing to the technology used for the reclamation of municipal wastewater because of its efficiency as well as its simple operation. In such a process, UF membranes are used for the secondary treatment of wastewater and RO acts as the polishing treatment step. The suspended solids are removed by UF membranes while RO membranes remove dissolved solids, organic and ionic matter. An MBR can achieve both the secondary treatment of sewage as well as the pretreatment for RO, and hence MBR–RO has a great potential for the treatment of raw sewage to produce reclaimable water [4,5].

In the pilot system, feed wastewater is pumped from the local sewerage network to the satellite wastewater treatment plant (WWTP). The inlet pumping station is feeding the sewage through a preliminary treatment that includes a compact fine screen–grit system and a biotube filter in the equalization tank of the system. The screens allow for the retention of solids and the grit–grease unit for the protection of the downstream equipment from sand particles, grease and oil. The outlet flow from the pretreatment unit enters via overflowing to the main treatment units. The main treatment units consist of biological treatment with MBR and finally an RO unit (Fig. 1).

The denitrification stage comes first and consists of an anoxic tank equipped with a proper mixing device that ensures mixing of the liquor. The mixed liquor from the denitrification tank enters the aeration tank where the biological processes of oxidation of the organic load, nitrification and stabilization of sludge are taking place. Separation of the suspended solids from the treated effluent is taking place through an UF membrane. The installed membrane consists of hollow fiber and UF modules. The pore's diameter is 0.03 μm, while the total filtration area of the membrane is 34 m^2. The modules operate under negative pressure with a filtration direction going from the outside of the hollow fiber

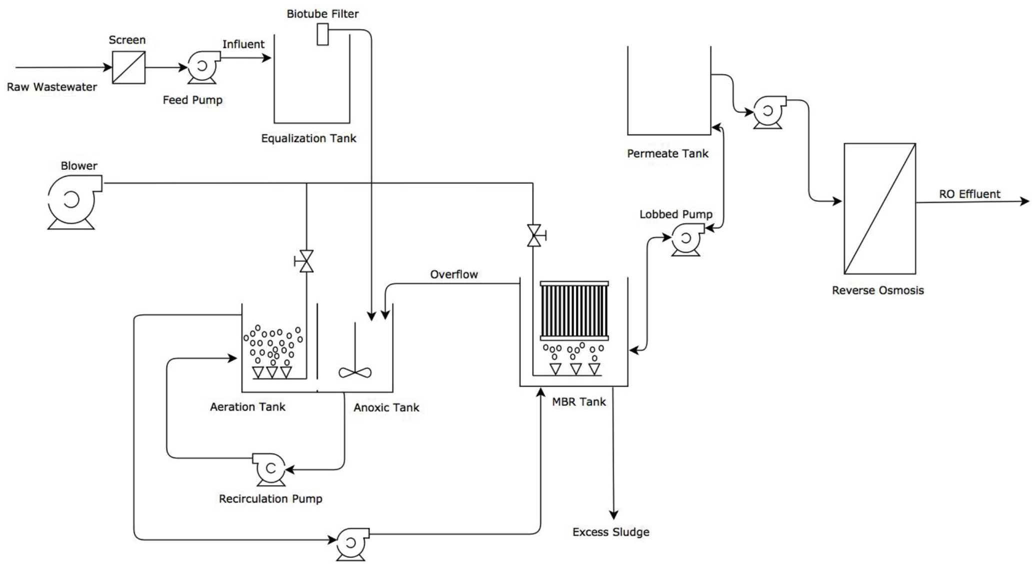

Fig. 1. Flow diagram of the MBR–RO pilot system.

toward the inside. Solids are therefore withheld in the retentate on the outside of the hollow fibers while the permeate flows inside and is collected by the collection manifold in the module to be subsequently conveyed to a permeate accumulation tank and then discharged. Excess sludge returns to sewage network. Discharge to wastewater collection system is a viable consideration where the retentate comes from a satellite treatment facility and the volume of the retentate is relatively small compared with the total flow of the central WWTP.

Cleaning of the membranes with air (air scouring) is performed through an aeration system that consists of blowers and coarse bubble diffusers. This operation protects the membranes from fouling and also ensures the smooth operation of the system, by removing the deposited – on the membranes – particles, thus allowing the filtration of the incoming wastewater. In order to maintain membrane permeability, two more methods of membrane cleaning have been applied. The first one is the backflushing mode, where the extraction pump inverts its rotation sense and conveys a part of the produced permeate from the inside to the outside of the hollow fibers to detach any material that may have been deposited on the outer surface of the fibers or inside the pores during the suction period. The second one is maintenance cleaning; chemical cleaning cycles consisting of sodium hypochloride (NaOCl) and citric acid reach the membranes by backflushing clean water that is enriched with those chemicals through dosage pumps. After leaving the membrane section, the permeate is driven into a tank by a lobed pump. From that tank it ends up to the RO system. RO systems are practically required to be incorporated in the treatment train (following MBR system) especially in the case of wastewater with high salinity. The need for RO as a posttreatment level derives from the necessity to comply with the environmental standards as in the case of saline wastewater. Moreover, the unit has the ability to work without RO treatment, in which case the permeate ends up directly into the effluent tank. A flow diagram of the pilot system is presented in Fig. 1, while Fig. 2 illustrates the MBR and the RO units.

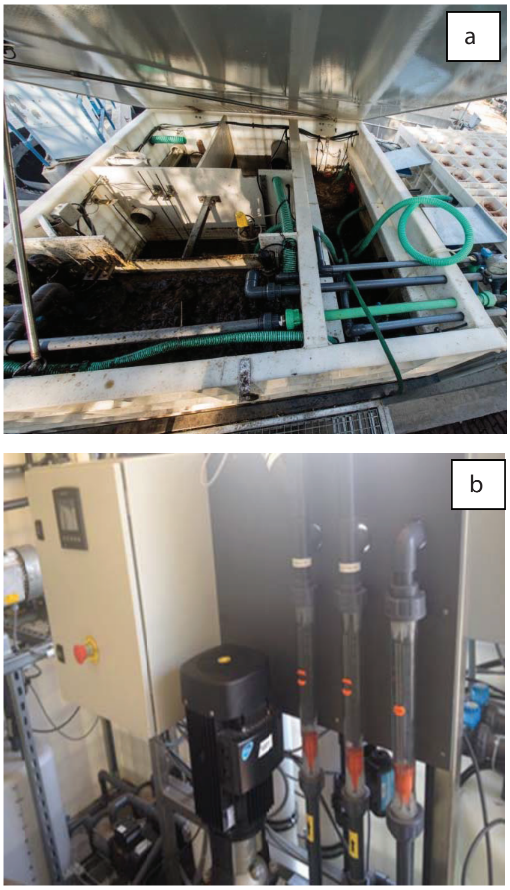

Fig. 2. Presentation of the pilot system (a) the compact unit containing (from the left to the right) the MBR, aeration, anoxic and equalization tanks and (b) the RO unit.

Table 1
Maintenance cleaning protocol

	Quantity (g/cycle)	Duration (min)
NaOCl (14%)	43	30
Citric acid (30%)	340	40

2.2. Operating parameters and monitoring system

The pilot unit has been set in operation for 8 months. During this period, temperature varied between 15°C and 25°C. The capacity of the unit was set to 10 m^3 of treated wastewater per day, while it has been designed to be able to reach up to 100 m^3/d. The concentration of mixed liquor suspended solids (MLSS) in the MBR tank was controlled between 8 and 9 g/L with daily removal of excess sludge in order to maintain a sludge retention time (SRT) of 20 d. Accordingly, MLSS concentration in the anoxic and aeration tank was almost constant at values around 6 g/L.

The operation cycle of MBR involved a 10 min filtration and a 1 min backflushing mode in order to preserve permeability. The maintenance cycles include one oxidizing cleaning per day and one acid maintenance per week. Table 1 presents the estimated chemical reagent consumption for membrane regeneration for the maintenance cycles.

One of the main advantages of the unit is the information and communication technology integration, which allows constant control and monitoring of the system by uploading data on an online platform. In order to control the quality of the process and the effluent, a series of online sensors have been installed at several key points of the unit, so as to provide perpetual information about the integrity of the operation. More specifically, conductivity meters have been installed in the inlet, permeate tank and RO effluent tank, pH sensors in the RO effluent and membrane tank, a turbidity sensor in the permeate tank, an MLSS sensor in the membrane tank, a dissolved oxygen sensor in the aeration tank and, finally, an ammoniacal nitrogen (NH_4–N) and nitrate nitrogen (NO_3–N) sensor in both the anoxic and aeration tanks.

Apart from using online sensors, a series of laboratory analyses provide feedback for the unit and many of them are used for cross-validation with the sensor measurements, thus providing feedback on the status of the online sensors. The laboratory analysis takes place twice a week, and includes measurements of total chemical oxygen demand

(CODt), soluble chemical oxygen demand (CODs), MLSS, mixed liquor volatile suspended solids, diluted sludge volume index (DSVI), biochemical oxygen demand (BOD_5), total phosphorus (TP), total nitrogen (TN), NH_4–N, NO_3–N, chlorides (Cl^-), total coliforms (TC), fecal coliforms (FC) and *Escherichia coli* (EC). In addition to the above measurements, samples from the inlet, permeate tank and RO effluent were frequently analyzed for emerging contaminants. Target compounds used in this study belong to the endocrine disrupting chemicals (EDCs) and the non-steroidal anti-inflammatory drugs (NSAIDs), compounds which present significant scientific interest due to their toxicological and chemical characteristics and their persistent detection in the aquatic environment. Table 2 presents the target compounds of this study chosen as representatives of EDCs and NSAIDs, along with their main physicochemical properties, their abbreviations and the limit of detection (LOD) for each compound.

2.3. Analytical methods

Wastewater characteristics (COD, BOD_5, total suspended solids (TSS), total volatile solids, sludge volume index, TP, TN, ammoniacal and nitrate nitrogen, chlorides, TC, FC and EC) were determined according to Standard Methods [6]. For the determination of the emerging contaminants, wastewater samples were analyzed using a chromatographic method developed by Samaras et al. [7]. The developed procedure included solid phase extraction, while for the qualitative and quantitative analysis, an Agilent Gas Chromatograph 7890A connected to an Agilent 5975C Mass Selective Detector was used.

3. Results and discussion

3.1. MBR performance and permeate quality

In order to promote the SM practice through the MBR–RO pilot system as a viable solution for non-potable water needs, especially in arid areas or highly urbanized environments, its excellent effluent water quality must be highlighted. To do so, both the operational performance and the water quality of the MBR and RO were evaluated. Furthermore, cross-validation of the produced water quality and the one demanded by the Greek legislation for water reclamation was also performed.

The pilot unit commenced operation in January 2016 without any biomass inoculation. The startup process lasted approximately 5 weeks, when the necessary conditions for biomass growth and nitrification–denitrification were established and approximately steady-state conditions were achieved (Fig. 3).

Based on the experimental results during the initial stages of the unit, the biotube seems to be acting efficiently as a filter for the removal of oils and other substances that can be proven harmful for the membranes. This is evidenced by the reduction of the COD from the feed wastewater to the filtered wastewater (Fig. 4). The characteristics of the degritted wastewater and the filtered wastewater entering the equalization tank are listed in Table 3. As can be seen from these data, pretreated wastewater characteristics exhibit significant fluctuations.

The operation of the MBR throughout the experimental period was stable and its performance was satisfactory. The effluent BOD_5 was always below 2 mg/L, while the average effluent total COD was as low as 23 mg/L, due to the very high removal averaging around 95% (Fig. 5(a)). This high removal rate is in good agreement with the study of Barreto et al. [8], who found out that due to its ability of functioning with high MLSS values, MBR can achieve removal rates of up to 99% for COD inlet values varying between 600 and 1,500 mg/L. Moreover, the nitrification process was almost complete, with NH_4–N concentrations reaching minimal values (Fig. 5(b)). The increased nitrification ability of the MBR is related with

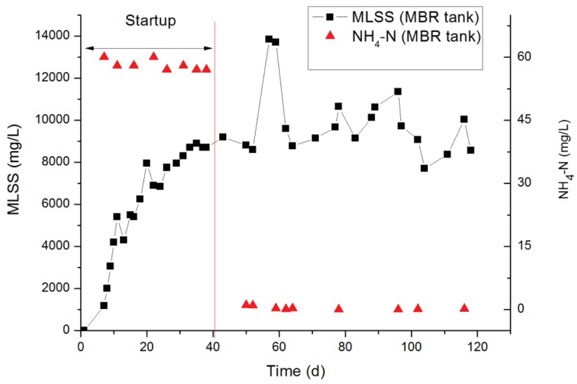

Fig. 3. Evolution of MLSS and NH_4–N concentrations in MBR tank.

Table 2
Target compounds, their physicochemical properties and their LOD (in ng/L)

Compound	Abbreviation	Molecular type	Molecular weight	LogK_{ow}	LOD
Nonylphenol	NP	$C_{15}H_{24}O$	220.36	4.5	3
Nonylphenol monoethoxylate	NP1EO	$C_{17}H_{28}O_2$	264	4.17	2
Nonylphenol diethoxylate	NP2EO	$C_{19}H_{32}O_3$	308	4.21	6
Bisphenol A	BPA	$C_{15}H_{16}O_2$	228.1	2.2–3.84	10
Triclosan	TCS	$C_{12}H_7Cl_3O_2$	290	4.2–4.76	4
Naproxen	NPX	$C_{14}H_{14}O_3$	230.27	3.18	3
Ibuprofen	IBU	$C_{13}H_{18}O_2$	206.29	3.91	1
Ketoprofen	KFN	$C_{16}H_{14}O_3$	254.3	3.12	0.5

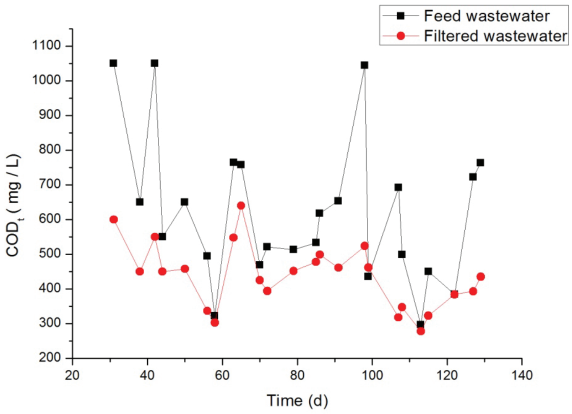

Fig. 4. Concentration of total COD in the feed and filtered wastewater.

Table 3
Characteristics of degritted and filtered wastewater (concentrations in mg/L, average ± standard deviation)

Parameters	Degritted wastewater	Filtered wastewater
TSS	376 ± 373	164 ± 72
Volatile suspended solids	235 ± 112	138 ± 46
CODt	578 ± 176	424 ± 86
CODs	173 ± 30	171 ± 25
TP	10 ± 1	8.8 ± 0.7
NH_4–N	57 ± 18	55 ± 15
Cl^-	184 ± 98	157 ± 23

the higher SRT achieved. In their research, Cote et al. [9] showed that an increase of the SRT from 5 to 10 d resulted in an increase of the ammonium removal rate from 80% to 99%, while Fan et al. [10] found that for the same increase in SRT, the nitrification efficiency increased from 94% to 99%.

The removal of suspended solids was complete, being always below the LOD, due to the fact that particle sizes are larger in relation to the membrane pores, so the particles are unable to penetrate through the membrane section. The achievement of minimal to zero suspended solids concentrations in MBR tank effluent is one of the benefits of these systems against conventional ones. In addition to that, the achievement of a permeate with practically constant characteristics is of high importance for the smooth operation of the RO unit, making the MBR system an ideal pretreatment to RO. Finally, the fact that the TSS in the MBR permeate stream was negligible within the 3 month evaluation span (as well as in the whole 8 months period), as seen in Fig. 5(c), in combination with the fact that transmembrane pressure (TMP) had a steady value of 2 kPa, indicate that the membrane remained intact, without appreciable fouling.

Throughout the operational period, all the key qualitative values (i.e., TSS, COD, BOD and turbidity) remained steady in the permeate flow, proving that the backflushing mode and the maintenance cleaning were very successful in maintaining the integrity of the membrane. That is the reason why, so far, recovery cleaning has not been necessary.

As illustrated in Fig. 5(d), it is clear that the unit operated at values of MLSS over 8,000 mg/L and despite the fact that the tank is small (1.5 m^3), MLSS concentration exhibited great stability. Cross-validation with the lab measurements revealed that the sensors provide trustworthy data. The accurate sensor measurements are very important as they allow the remote control of the unit and provide its safety by leading to alarm conditions and ultimately to unit shutdown – if needed – when key values overcome the programmed upper threshold.

Fig. 6(a) presents the variation of turbidity throughout the examination period. The online data from the sensor showed that the turbidity mostly retained values below 2 NTU, while the average value was around 0.3 NTU. An important fact that has to be mentioned is that the retrieved values refer to the same time as the lab sampling took place, specifically at around 9:30 am. The spike occurring around day 100 might imply the existence of a breach in the membrane, which is usually accompanied by an increase of microorganisms [11]. This is one of the main reasons that highlight the importance of continuous monitoring of turbidity as an indicator of microorganism concentration. Fig. 6(b) shows the intraday variation of turbidity for six random days within the 3-month span of monitoring. The spike in turbidity values in this graph is not correlated with any type of membrane breaching, but rather with the daily scheduled maintenance cleaning. This argument is consistent with the study of Branch et al. [12], which showed that after cleaning in place, turbidity immediately increases and returns to its average values after about 4 h.

The settling characteristics of biomass were satisfactory throughout the experimental period, as evidenced by the DSVI values (Fig. 6(c)). More specifically, DSVI ranged between 60 and 140 mL/gSS with an average value of 100 mL/gSS, thus indicating a biomass with acceptable settling properties [13].

MBR membranes have been reported to achieve an important decrease in microorganism concentration, varying from 4 to 8 log units, mainly through size exclusion [14]. The parameters that were chosen as representative indicators and thus were regularly monitored in the MBR permeate and RO effluent were the TC and FC, as well as EC. These parameters were chosen because they are representative indicators for the existence of other microorganisms. More specifically, a reduced concentration of coliforms in general reveals the absence of other microorganisms and FC have additionally been correlated with the existence of fresh fecal matter, while the decrease of EC are related to the absence of virus [11]. Fig. 6(d) shows that EC and FC were below the LOD, which indicates that the membrane remained intact during the operational period. Furthermore, the TC content of the MBR effluent was rather low, with values around 300–350 cfu/100 mL. The presence of such a low TC content in the MBR effluent might be due to the formation of microbial colonies in the permeate's pipeline [11]. These results are in good agreement with the results reported by Zhang and Farahbakhsh [15], who attribute high TC values to the formation of biofilm in the internal space of the permeate pipeline.

Fig. 7(a) presents the average concentrations and the standard deviation of the target emerging contaminants in the influent wastewater, in the effluent of the MBR tank and

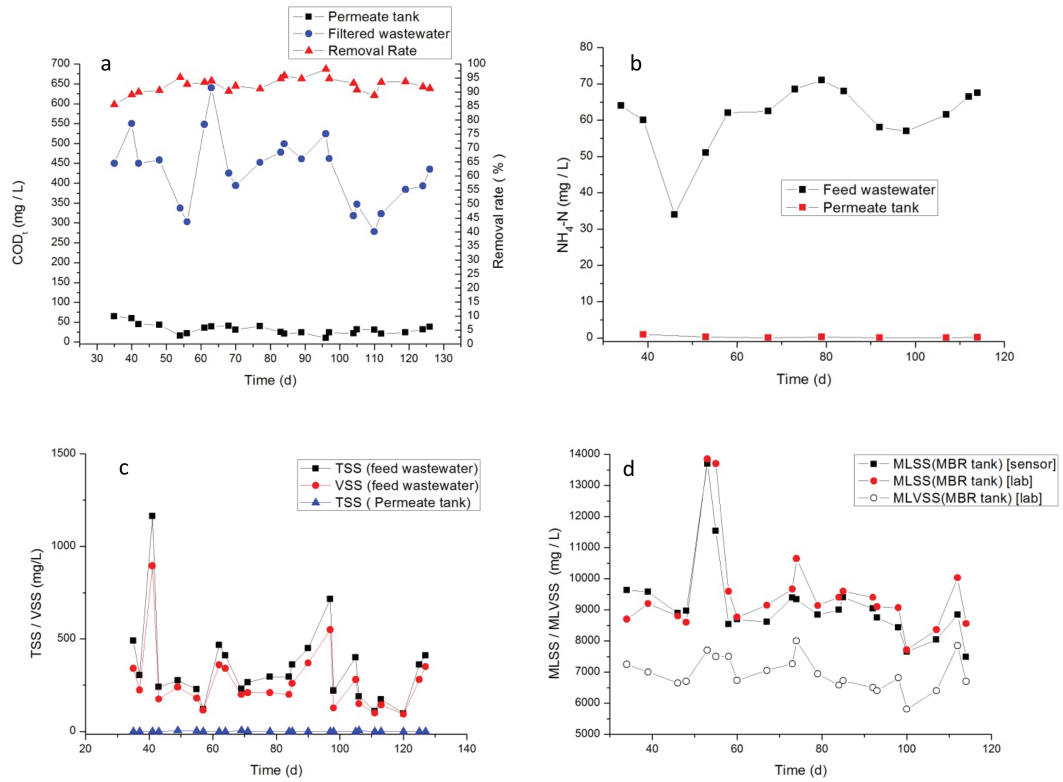

Fig. 5. MBR performance throughout the experimental period (a) CODt, (b) NH_4–N, (c) TSS and (d) MLSS.

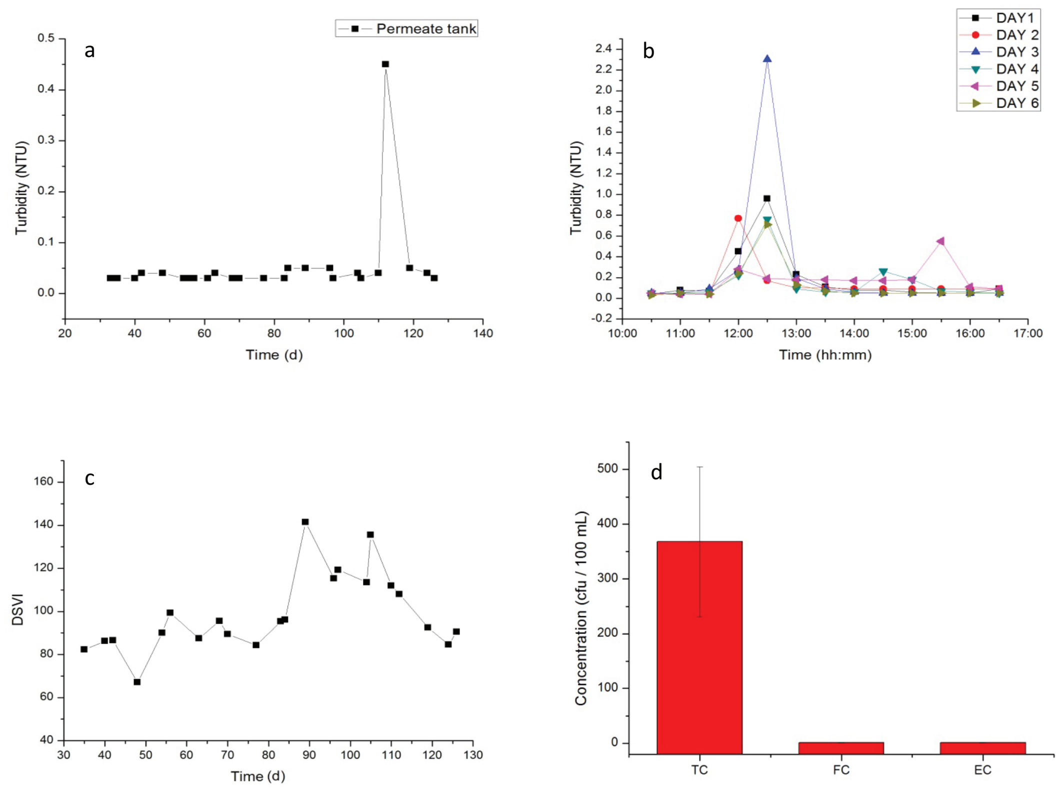

Fig. 6. Variance of (a) inter day turbidity, (b) intraday turbidity, (c) DSVI and (d) average values of microbial parameters in the permeate flow.

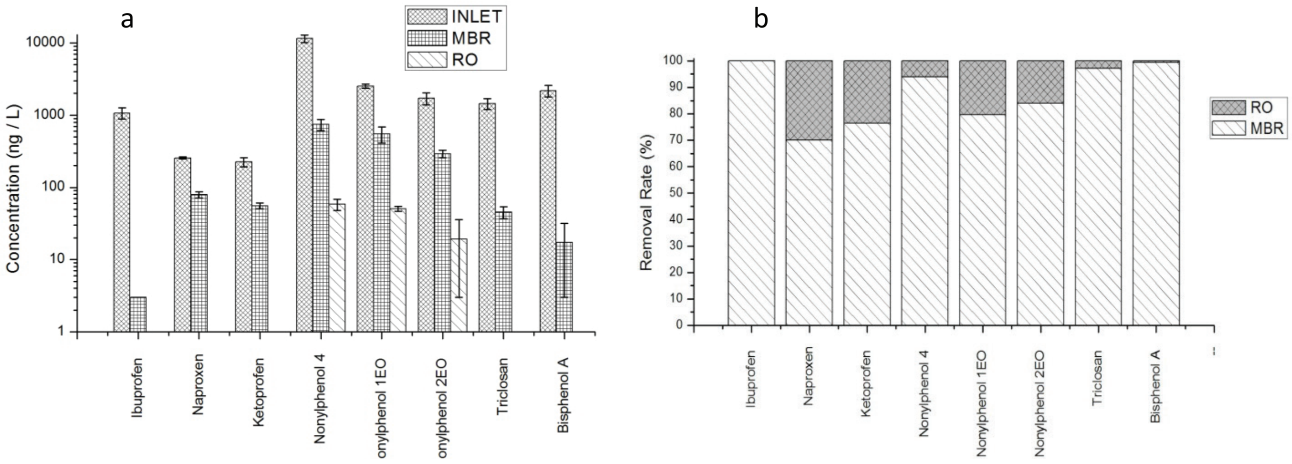

Fig. 7. (a) EDCs and NSAIDs average concentrations in the inlet, MBR permeate and RO effluent and (b) contribution of MBR and RO to the total removal of EDCs and NSAIDs.

the final effluent (RO effluent), while Fig. 7(b) exhibits the relative contribution of the removal of each target compound at the MBR and RO unit. Based on the results, the MBR tank achieved a removal of greater than 99% for ibuprofen (IBU), greater than 90% for triclosan (TCS) and nonylphenol (NP), greater than 80% for nonylphenol diethoxylate (NP2EO), whereas the removal of all the other target compounds was greater than 70%. Besides their high removal, the MBR effluent concentrations of NP and its ethoxylates (nonylphenol monoethoxylate [NP1EO] and NP2EO) were rather high (to the order of 200–800 ng/L). These results were expected, since in UF filtration the removal of EDCs and other organic compounds is achieved through the absorption of the substances from particulate matter and thus only hydrophilic substances can be removed, while more polar molecules present a lower removal rate (due to small SRTs). On the contrary, nanofiltration removes such particles through size exclusion [16]. In any case, NP permeate concentration was lower than the threshold value of 2 μg/L, which has been set in the Greek legislation for NP for wastewater reuse for WWTPs with a population equivalent greater than 100,000.

3.2. RO performance and effluent quality

The performance of the RO is such that superior water quality was achieved in the final effluent. As illustrated in Table 4, all the microbiological indicators remained under the LOD. The RO effluent did not show any presence of EC or TC, indicating their complete rejection. Moreover, chlorides are less than a quarter in comparison with the RO inlet. Other parameters that remain under the LOD are COD and TP. Regarding the presence of EDCs and NSAIDs in the effluent stream, Fig. 7(a) shows that for almost every compound, its concentration lied under the LOD. The only exceptions to that where NP, NP1EO and NP2EO, for which RO managed a 2-log reduction. Based on the data presented in Fig. 7(b), more than 94% of NP, TCS, bisphenol A (BPA) and IBU removal is taking place in the MBR, while in the case of NP1EO and NP2EO the respective values were to the order of 80%–84%. On the other hand, the contribution of the RO unit to the total removal of naproxen (NPX) and ketoprofen (KFN) was more profound (contributing 24%–30% of the total removal of the target compounds).

The installed online sensors monitor the pH and conductivity of both the inlet and effluent of the RO. Conductivity is the single most important and most commonly monitored system parameter in an RO plant. The RO flux and recovery rate are greatly affected by the conductivity of the feed water. As conductivity rises, the same happens with osmotic pressure, thus making the RO system less efficient at a given pressure and temperature. Therefore, the installation of online sensors is of great importance, since they provide for the identification of changes in permeate flow rate due to feed conductivity fluctuations [17]. Based on the experimental results, conductivity remains unaffected by the MBR, but was drastically reduced by the RO. In order to evaluate the performance of the RO in terms of effluent pollutant concentrations, rejection in terms of conductivity was used, which is defined as the percentage difference between the conductivity of the feedwater and that of the effluent. The rejection averages at values over 90% (Fig. 8(a)). The same pattern was recorded for pH (Fig. 8(b)). It should also be mentioned that both conductivity and pH in the RO effluent kept increasing in time while rejection rate decreased. This indicates that the RO membranes have sustained fouling or scaling, although anti-scalants were added regularly into the system in order to minimize chemical precipitation on the RO membrane surface [18].

3.3. Reuse options cost estimation

Table 4 presents the quality characteristics of the MBR effluent and the final effluent (RO effluent) of the experimental system along with the limit values as specified in the Greek National legislation regarding wastewater reuse for unrestricted irrigation and urban use (JMD 145116/2011).

It is evident that the MBR effluent characteristics lie within the limits set in the Greek wastewater reuse legislation for unrestricted irrigation. Its EC and FC content is minimal, while its TC content is low. According to our experience, a rather low chlorine or UV dose is required in order to achieve the strict effluent threshold value for TC set in the Greek

Table 4
Performance of the MBR–RO pilot system (concentrations in mg/L, NP in ng/L, TC, FC, EC in cfu/100 mL, turbidity in NTU)

Parameters	Influent[a]	MBR effluent	RO effluent	Legislation limits[b]
TSS	164 ± 72[c]	<LOD[g] for 80% of samples	<LOD[g]	≤2 for 80% of samples[e] ≤10 for 80% of samples[d]
BOD_5	141 ± 64[c]	0.9 (average) 1.6 for 80% of samples	≤1 for 80% of samples	≤10 for 80% of samples[d,e]
CODt	424 ± 86[c]	23 ± 9.5[c]	<10 (average)	
CODs	171 ± 25[c]	23 ± 9.5[c]	<10 (average)	
TN	81 (average)	–	12 (average)	≤15[d,e]
NH_4–N	55 ± 15[c]	0.25 ± 0.3[c]	–	≤2[d,e]
TP	8.8 ± 0.7[c]	5.9 ± 1[c]	<0.5	
Turbidity	–	0.04 (median)	–	≤2 (median)[d,e]
TC	>10^7	307 ± 390[c] 578 for 80% of samples 1,115 for 95% of samples	ND[h]	≤2 for 80% of samples[e] ≤20 for 95% of samples[e]
FC	>10^7	1 ± 1.8[c]	ND[h]	–
EC	>10^7	0.8 ± 1[c] ≤2 for 80% of samples ≤2 for 95% of samples	ND[h]	≤5 for 80% of samples[d] ≤50 for 95% of samples[d]
NP	11,542 (average) 13,705 (maximum)	747 (average) 968 (maximum)	58 (average) 75 (maximum)	<2,000 (maximum value)[f]

[a]Filtered wastewater.
[b]The Greek legislation regarding wastewater reuse (Joint Ministerial Decision 354/8-3-2011).
[c]Average ± standard deviation.
[d]The limit values set in the Greek legislation for wastewater reuse for unrestricted irrigation and/or industrial reuse.
[e]The limit values set in the Greek legislation for urban reuse and/or groundwater recharge.
[f]The limit value set in the Greek legislation for every type of reuse for WWTPs with a population equivalent greater than 100,000.
[g]Limit of detection.
[h]Not detected.

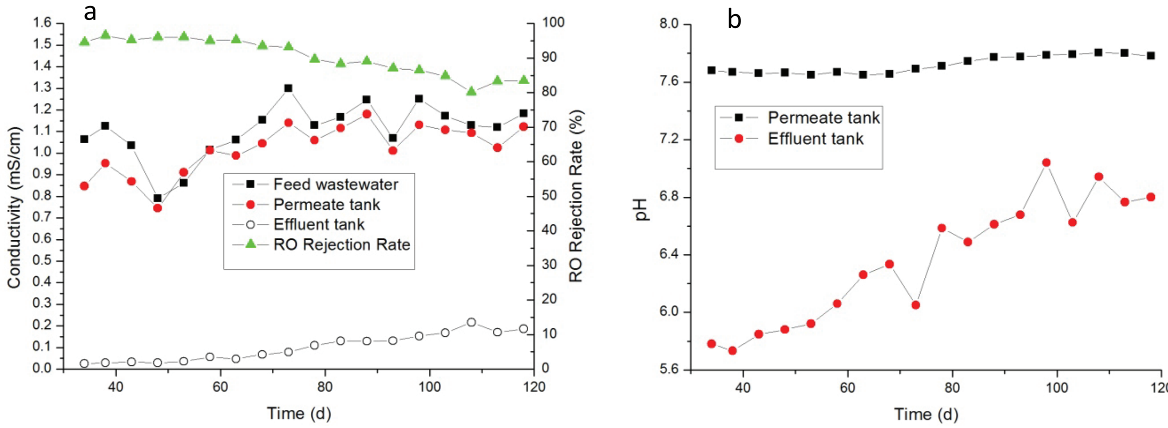

Fig. 8. Evolution of (a) conductivity and (b) pH in the RO effluent.

legislation for urban reuse (≤2 for 80% of samples and ≤20 for 95% of samples) [19]. Therefore, it is anticipated that in order to achieve effluent characteristics suitable for every possible non-potable use, MBRs should always be followed by a disinfection unit, which in the case of SM procedure, would be better if it were in the form of a UV unit (with a minimum UV dose of 50 mW s/cm^2 at the end of the life of the lamps).

A vital issue that has to be addressed in the water reclamation process is the capital and operational cost of a unit. For this purpose, data concerning the capital and operational cost of the pilot unit were used in order to project expenses to the case of retrieving 100 m^3 of wastewater per day. Furthermore, two scenarios were examined; one where the system consists of an MBR and the other one considers the use of an MBR unit followed by RO, both followed by UV for disinfection purposes. The life span of the unit was considered to be 15 years and the discount rate was assumed 2%. According to the calculations performed, for the first scheme mentioned, the total capital cost amounts to 167,000 € (including contractor benefits), while the operational cost amounts to 0.5 €/m^3, which produces a total cost of 0.86 €/m^3. For the RO-involving scheme, the total capital cost amounts to 200,000 € (including contractor benefits), with an operational cost of around 0.65 €/m^3, and when combined, the operational and capital expenses form the price of 1.07 €/m^3. The aforementioned calculations are presented in Table 5.

According to the literature, DESSIN unit appears to be more cost-efficient comparing it to similar units. When compared with the compact system installed in Flemington Racecourse, Melbourne, which consists of microfiltration dual membranes followed by RO, DESSIN's unit seems to be more cost-efficient [20]. More specifically, the aforementioned system has the capacity of 100 m^3/d, with a capital cost of $350,000, while the operating cost amounts to 0.6 $/m^3 (prices 2006). When compared with a moving bed biofilm reactor followed by both RO and UV installed in Darling Quarter, Sydney, the difference becomes more evident. For a total capacity of 170 m^3/d, that particular unit has an operational cost of 2.1 $/m^3, while the capital expenses are similarly high; 2.2 $/m^3 (prices 2011) [21]. The full potential of the MBR–UV scheme can be observed in the unit installed in Pennant Hills, Sydney, where the upscaled unit produces 1,000 m^3 retrieved water per day with a mere 0.49 $/m^3 capital cost (prices 2008) [22].

The presented characteristics of the effluent water, coupled with the compact nature of the system that neither requires other than the existing infrastructures nor plenty space, make this SM unit suitable for use in tourist facilities, golf courses or municipalities within the urban network, following the example of multiple SM establishments in Australia [23,24]. However, the cost data provided above pointed out the feasibility of the employment of such units by small and medium enterprises who wish to enter the water supply market. This prospect can be backed by the fact that, in the case of Europe, the expected rate of gross domestic product growth of the water sector is expected to be around 0.2%–0.6%, due to investments in the water industry alone, in order to conform to the Water Framework Directive [25]. Such an idea can be implemented by installing several such units in a neighborhood scale, in order to meet local needs. In such a case, it has to be noted that as the number of units in operation increases, the operating cost decreases, since several units can be managed simultaneously by a single operator, given the installed automations and the online monitoring system. Adding to that, due to scale economy, the capital expenses per unit will also degrade, giving room to more competitive selling prices.

In view of the above, it is concluded that the application of SM practice through the implementation of an on-site compact treatment system consisting of a pretreatment unit followed by an MBR and a UV disinfection unit can reliably meet all the national and international criteria set for all types of non-potable wastewater reuse at a rather moderate cost. On the other hand, the application of the integrated MBR–RO system, despite achieving a very high quality effluent, is still a rather luxurious option. The addition of an RO unit is fully justified in the case of saline wastewater. In any case, additional measurements are required with respect to the heavy metals and priority pollutants content of the treated effluent in order to select the most appropriate treatment scheme.

Table 5
Presentation of the cost per m^3 of retrieved wastewater for both MBR–UV and MBR–UV–RO schemes

	MBR–UV	MBR–UV–RO
Capital cost (€/m^3)	0.36	0.42
Operational cost (€/m^3)	0.5	0.65
Total cost (€/m^3)	0.86	1.07

4. Conclusions

Double-membrane treatment schemes (MBR–RO) allow for the achievement of a very high quality treated effluent suitable for every type of reuse. The system presented very satisfactory operational stability and great performance. The elimination of organic carbon and pathogenic content was complete. The filtration process managed reduction of pathogens without the addition of chemicals, thus avoiding the production of secondary pollutants. So far, TMP remains steady at low values, proving that the combination of backflushing with maintenance cleaning is very effective. Based on the experimental results, it is concluded that the application of SM practice through the implementation of an on-site compact treatment system consisting of a pretreatment unit followed by an MBR and a UV disinfection unit can reliably meet all the national and international criteria set for all types of non-potable wastewater reuse at a rather moderate cost. The application of the integrated MBR–RO process is financially justified only in the case of saline wastewater.

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