Modeling Energy Consumption in Membrane Bioreactors for Wastewater Treatment in North Africa

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ABSTRACT: Two pilot-scale membrane bioreactors were operated alongside a full-sized activated sludge plant in Tunisia in order to compare specific energy demand and treated water quality. Energy consumption rates were measured for the complete membrane bioreactor systems and for their different components. Specific energy demand was measured for the systems and compared with the activated sludge plant, which operated at around 3 kWh m^{-3}. A model was developed for each membrane bioreactor based on both dynamic and steady-state mass balances, microbial kinetics and stoichiometry, and energy balance. Energy consumption was evaluated as a function of mixed-liquor suspended solids concentration, net permeate fluxes, and the resultant treated water quality. This work demonstrates the potential for using membrane bioreactors in decentralised domestic water treatment in North Africa, at energy consumption levels similar or lower than conventional activated sludge systems, with the added benefit of producing treated water suitable for unrestricted crop irrigation. *Water Environ. Res.*, **86,** 232 (2014).

KEYWORDS: membrane bioreactor, energy consumption, specific energy demand, decentralised domestic waste water treatment.

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Introduction

Energy consumption is an increasingly important factor in the wastewater treatment (WWT) sector, which can sometimes affect the viability of the treatment method. Regarding aerobic biomass separation membrane bioreactors (MBRs), the first-generation side-stream configurations required more energy than the conventional activated sludge (AS) processes. Side stream MBRs have been reported as having specific energy demand (SED) values between 4 kWh m^{-3} and 12 kWh m^{-3}, whereas AS processes typically operate with SED values between 0.2 kWh m^{-3} and 0.4 kWh m^{-3} (Zhang et al., 2003; Liao et al., 2006). Side-stream MBRs require large amounts of energy to generate the cross-flow velocity across the membrane modules, as well as maintaining the required trans-membrane pressure (TMP) for filtration (Gander et al., 2000; Stephenson et al., 2000; Van-Der-Roest et al., 2002). This increased energy consumption was initially one of the main disadvantages of the MBRs (Water Environment Federation, 2006) that prohibited their widespread application.

The second-generation submerged configurations, first introduced to the market in 1989, succeeded in reducing these high energy costs, and today their energy consumption rates are quite competitive with those of the traditional WWT processes (Van't-Oever, 2005; Guglielmi et al., 2007). In submerged MBRs, energy consumption rates appear to be lower than 1 kWh m^{-3} (Ndinisa et al., 2006); however, the literature reports a very wide range *i.e.* between 0.2 kWh m^{-3} and 4.0 kWh m^{-3} (Howell et al., 2004; Liao et al., 2006; Verrecht et al., 2010).

In submerged membrane bioreactor (MBR) configurations, energy consumption requirements usually come from liquid pumping, the application of permeate suction if necessary, and aeration of the MBR units for both membrane cleaning and to provide oxygen for the micro-organisms. In gravity-driven submerged MBRs, the application of suction is not necessary as the hydraulic head above the membranes is adequate to maintain filtration. Energy is then consumed by feed pumps and by the air blowers which produce turbulent aeration to scour the membranes to limit both concentration polarisation and membrane fouling phenomena. Additionally, it provides good mixing to prevent settling of biomass, and supplies enough oxygen to maintain the biomass (Gander et al., 2000; Puratreat Project: Deliverable 3, 2007). Suction pumps have to be included for submerged MBRs where gravity is not adequate to drive filtration, (Ueda and Hata, 1999). However, it is the air blowers that have been reported to be the most energy-consuming devices accounting for around 50% (Ndinisa et al., 2006), or 80% (Chua et al., 2002; Howell et al., 2004; Schoeberl et al., 2005; Meng et al., 2008), or even 90% to 100% (Gander et al., 2000; Stephenson et al., 2000) of the overall MBR energy consumed.

Attempts to simulate energy requirements in MBR systems have also been made. Current MBR models mainly simulate either biomass kinetics or membrane fouling but there are also integrated models that combine both of them so that they can describe the complete MBR process (Ng and Kim, 2007). However, there are some MBR models that additionally include important energy-related issues. In 2008, Zarragoitia-Gonzalez *et al.* developed a mathematical model to simulate filtration and the aeration influence on submerged aerobic MBR systems. The model linked the activated sludge bio-kinetics, aeration and membrane fouling process and was able to study membrane fouling under different MBR operating conditions and to optimise the aeration/filtration cycles, which consequently

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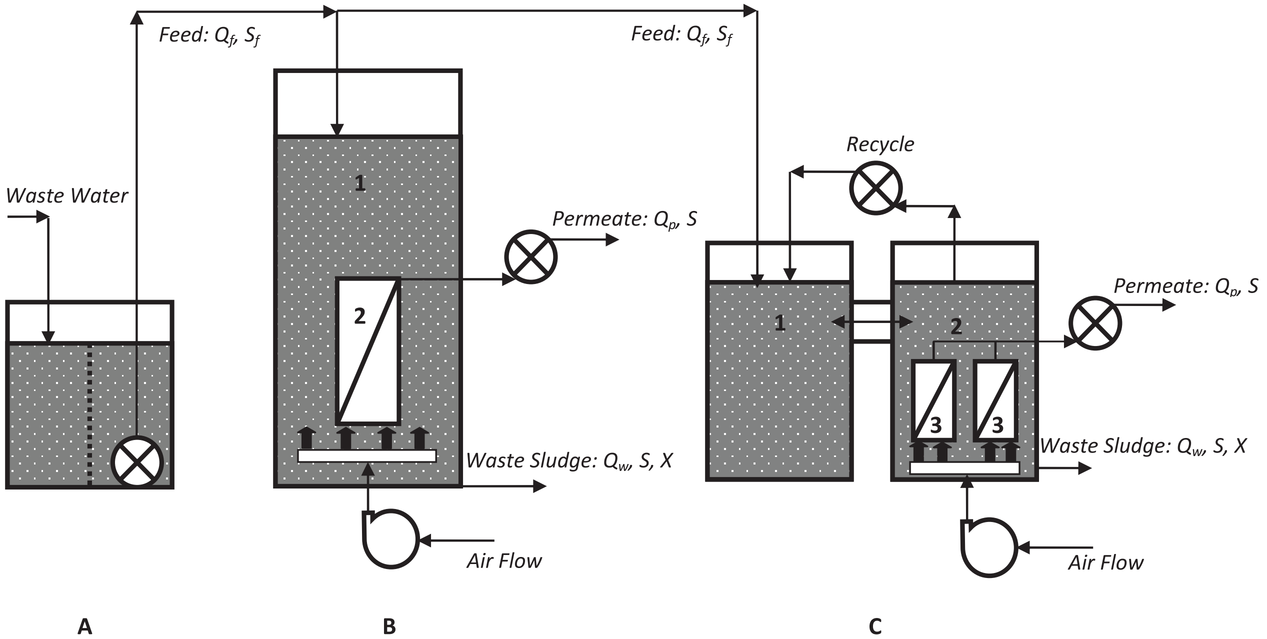


Figure 1—A schematic of the MBR process set-up.
Key: A. Anoxic zone with screen for both MBRs; B. MBR_1: 1. MBR tank, 2. Membrane module; C. MBR_2: 1. Biological treatment tank, 2. MBR tank, 3. Membrane modules, Q_f: Volumetric feed flow rate, S_f: Feed substrate (feed COD) concentration, Q_p: Volumetric permeate flow rate, S: MBR substrate (treated water COD) concentration, Q_w: Volumetric waste sludge flow rate, X: Biomass (MLSS) concentration.

reduced running costs for aeration (Zarragoitia-Gonzalez et al., 2008). A model for evaluating energy demand that arises from aeration of an immersed MBR was developed by Verrecht *et al.*, in 2008. The aeration energy model showed that significant reduction in aeration energy could be obtained through operation at lower fluxes and reduction in the membrane aeration requirement accordingly (Verrecht et al., 2008). Finally, Suh *et al.*, in 2013, developed an integrated model that evaluated different membrane fouling control conditions in submerged MBRs. That model also incorporated an aeration model and was able to calculate the MBR energy requirement. It then proved that the largest contribution to energy consumption was the energy for aeration used to scour the membranes (Suh *et al.*, 2013).

In this work, energy-analysis experiments were performed with respect to the operation of two pilot-scale submerged MBR units (Figure 1), one with gravity-driven filtration and the second operating with a permeate suction pump. Energy consumption rates for each MBR component were measured initially; then, overall energy consumption rates and SED values were calculated. An MBR model was developed based on mass balances in combination with microbial kinetics and stoichiometry, and the energy balance. It was calibrated and validated against experimental data collected over a 9-month period. A range of solids residence times (SRTs) and hydraulic residence times (HRTs) were then evaluated using the MBR model in order to predict SED values, together with treated water quality (effluent chemical oxygen demand (COD) concentration values), mixed-liquor suspended solids (MLSS) concentrations, and necessary membrane permeate fluxes (MPFs). The experimental results and the model demonstrate that MBR units can be competitive with conventional AS processes in Tunisia, or perhaps more generally in the Middle East and North Africa (MENA) region.

Materials and Methods

Characteristics of the Pilot MBRs. This work was part of the PURATREAT Project, “New Energy Efficient Approach to the Operation of Membrane Bioreactors for Decentralised Waste Water Treatment”. The PURATREAT Project was funded by the European Union (EU) with partners across Africa, Asia and Europe. Its objective was to study a new approach to the operation of MBRs including a comparison of current MBR technologies. The operating procedure to be studied was expected to yield very low energy consumption and reduced maintenance costs. These characteristics would make the MBRs working in these conditions suitable for operation in peri-urban areas of the Mediterranean basin, where expenditure in public services is a critical factor (www.puratreat.com, 2013).

Two pilot MBR systems were located at North Sfax “Office National de l’Assainissement” (ONAS) site in Sfax in Tunisia. ONAS is the country’s Sanitation Utility and, at the North Sfax site, it operates a full-scale conventional AS plant treating municipal waste water. Membrane bioreactor 1 (MBR_1) was provided by Eimco Water Technologies (now Ovivowater). It was a gravity-driven system with a total operational volume of 1.38 m^3. It was equipped with seven standard Kubota flat sheet (FS) membranes operating in the micro-filtration (MF) range (nominal pore size of 0.4 μm) placed 7 mm apart, providing a total filter area of 5.6 m^3 (www.ovivowater.com, 2012). Membrane bioreactor 2 (MBR_2) was provided by Weise Water Systems GmbH. It was a suction-driven system with a total operational volume of 2.02 m^3. MBR_2 was equipped with two MC03 MicroClear® FS membrane filters operating in the ultra-filtration (UF) range (nominal pore size of 0.04 μm). Each filter

Table 1—Operating conditions of the MBR systems during the experiments.

Parameter	MBR_1	MBR_2	Unit
Operating volume	1.38	2.02	m^3
Operating membrane area	5.6	7	m^2
SRT	15 - 30	15 - 30	d
HRT	0.84 - 1.01	0.84 - 1.01	d
Air flow rate within the biological treatment tank	-	6	$m^3\ h^{-1}$
Air flow rate within the MBR tank	4.2	12	$m^3\ h^{-1}$
Aeration method	Coarse bubble	Fine bubble	-
Filtration cycle	10/0	9/1	min on/min off

Key: HRT: Hydraulic Residence Time, MBR: Membrane Bioreactor, MBR_1: Membrane Bioreactor 1, MBR_2: Membrane Bioreactor 2, SRT: Solids Residence Time.

consisted of 24 FS membrane panels spaced 5 mm apart with a total filter area of 7 m^2 (www.weise-water-systems.com, 2012). Further details about the MBR equipment and operating conditions tested in the trials are given in Table 1. Both MBRs were operated on the same feed wastewater, which was municipal waste water following pre-treatment with oil/fat and sand/grit removal, followed by fine screening.

MBR_1 was a single-tank system with the tank acting both as a biological treatment tank and also housing the membranes; it used a hydraulic head to drive permeation through the submerged membranes. Pre-treated wastewater was fed into the MBR using a feed pump connected to a level control switch in the MBR tank. The permeate rate was regulated by a variable control valve linked to a flow meter, and sludge was wasted manually on a regular basis. Hence, solids residence time (SRT) and hydraulic residence time (HRT), and consequently MLSS concentration and membrane permeate flux (MPF) could be maintained. Membrane permeation was continuous, and the gassing rate was selected as per the standard for Kubota systems (Table 1).

MBR_2 was a two-tank system, with the first tank providing biological treatment and the second tank housing the membrane modules. The tanks were linked via a recirculation pump and an overflow from the second to the first. Wastewater was fed to the MBR by a feed pump, linked to a level control switch in the MBR. Permeate was removed through the membranes by a suction pump, which was regulated by a flow meter in the permeate line, and sludge was wasted manually on a regular basis. Again, SRT and HRT, and consequently MLSS concentration and MPF could be maintained. Membrane permeation was intermittent, with a cycle time of 9 minutes filtration and 1 minute relaxation, and the aeration rate was fixed in relation to the supplier's operating instructions (Table 1).

In both systems, parameters such as TMP, MPF and energy consumption could be recorded automatically via data loggers. Sampling of feed water and treated water was conducted on a regular basis to establish water quality (influent/effluent COD concentration measurements), and the MLSS concentration in the MBRs was also measured regularly. In this research, MLSS concentrations were measured using the 2540 standard methods for the examination of water and wastewater. The COD concentrations were measured using the 5220 standard methods (Standard Methods for the Examination of Water and Waste Water, 2005). Dissolved oxygen concentration within the tanks was not monitored as its detailed measurement was not part of this work. However, it was clear that the aerobic bacterial cultures never suffered from lack of oxygen during the experiments as the COD concentration measurements in the influent and effluent showed that bacteria were always active—the organic matter in the effluent was below or at the COD concentration expected in a completely treated effluent (< 100 mg L^{-1}).

The MBRs were tested over a 9-month period, with two steady state periods being achieved, one at an SRT of 15 d and an HRT of 1.01 d, and the other with the same HRT but an SRT of 30 d. The 15-day SRT led to an average MLSS concentration of 4 g L^{-1} to 5 g L^{-1}, and the 30-day SRT led to an MLSS value of around 9 g L^{-1} to 10 g L^{-1}. Each time a rapid unexpected TMP rise was observed in either MBR during this 9-month period, membranes were facing severe membrane fouling; so, membrane cleaning had to be applied. First, membranes were cleaned using a physical cleaning process that interrupted filtration but continued membrane scouring. Filtration was reinstated after cleaning and the changes in TMP were monitored. If TMP could not stabilise at lower values but its values started increasing exponentially once again soon after the physical cleaning, the physical cleaning had to be deemed unsuccessful and the membranes had to be cleaned chemically. During a chemical cleaning, filtration was suspended and membranes were soaked in NaOCl solutions.

This paper focuses on aspects of the trials that concentrated on the performance of the two pilot MBRs in terms of their energy consumption, and comparing this aspect and treated water quality to the full-sized AS plant. However, it has to be stated that, even though the application of a membrane cleaning (physical or chemical) may lead to improved energy consumption rates, its effect on SED values was not analysed in this research.

Energy-analysis Experiments

Both short-term component-based energy-analysis experiments and longer-term energy-analysis experiments were carried out with the aid of in-line digital electricity meters. These energy-analysis experiments were conducted to measure the energy consumption rates of the MBR systems, and then calculate their SED values, with the SED value defined as energy consumed per volume of treated water. During the short-term component-based energy-analysis experiments, the average power value for each MBR component was instantly recorded by the in-line digital power meters. The energy-consuming components of MBR_1 system comprised a control panel, an air blower, and a feed pump. The MBR_2 system comprised a control panel, a biological treatment tank air blower, two membrane scouring air blowers—one per membrane module—and feed, recirculation and suction pumps. As the operating runtime of each MBR component over a day was also known, the energy consumption rate of each individual MBR component throughout a day was calculated by simply multiplying the average power value for a component with the corresponding runtime. The overall energy consumption rate for each MBR system was calculated by adding these energy consumption rates together.

During the longer-term energy-analysis experiments (no component-based analysis was made during these experiments), the amount of energy that was consumed by the MBR systems was recorded over a longer period (over a week) using the in-line digital power meters. Dividing the energy consumption reading by the time, and normalising the quotient over a day, provides the daily amount of energy consumed by each MBR system. Mains electricity consumption was also recorded using rotating-counter electricity meters and also normalised over a day. This allowed validation of the data collected by the in-line digital power meters when used for individual components as well as the complete systems.

By dividing the daily energy consumption rate by the net permeate flow rate over a day, a SED value for each MBR system can be obtained. A direct comparison between the two MBR systems can then be made, and comparisons were also made against the energy consumption of the full-sized AS system.

Finally, if necessary, for any set of operating conditions, energy consumption rates in kWh d^{-1} and SED values in kWh m^{-3} could be predicted through the development of an Excel spreadsheet based on the power values measured during the short-term component-based energy-analysis experiments. Energy consumption rates were calculated by multiplying the measured power rating for each component by the corresponding runtime. For example, energy consumption rates for the constant speed feed pumps were calculated for different feed flow rates by multiplying the recorded power rating by the runtime. Power consumption was measured at varying flow rates for the MBR_2 permeate suction pump and a linear correlation applied. The MBR_2 recirculation pump and air blowers for both MBRs were operated as specified by the suppliers, and their runtimes coupled with power ratings provided corresponding energy consumption data. Finally, energy consumption data was normalised to time to account for the different operating cycles for the different components on each MBR system. The energy models for each MBR system predicted actual energy consumption to within 1% throughout the range tested.

MBR Modelling

Dynamic MBR Modelling - Evaluation of Kinetics and Stoichiometry. A dynamic model of the MBR systems was set up using Mathcad 15 (PTC Corporation). The model was set up as follows:

Assumptions (for both MBRs):

(1) Operation at constant volume, which means:

$$Q_f = Q_p + Q_w \tag{1}$$

where:

Q_f: Volumetric feed flow rate in $m^3\ d^{-1}$
Q_p: Volumetric permeate flow rate in $m^3\ d^{-1}$
Q_w: Volumetric waste sludge flow rate in $m^3\ d^{-1}$

(2) There is no effective biomass in the feed stream.
(3) Sufficient oxygen is supplied to the biomass in the tanks, and that therefore growth is limited by the COD concentration in the bioreactor.
(4) Monod kinetics with cell death has been applied:

$$\mu = \frac{\mu_{max} S}{(K_S + S)} - k_d \tag{2}$$

where:

μ: Specific biomass growth rate in d^{-1}
μ_{max}: Maximum specific growth rate in d^{-1}
S: MBR substrate (treated water COD) concentration in g m^{-3}
K_S: Half-velocity (substrate affinity) constant in g m^{-3}
k_d: Endogenous decay co-efficient in d^{-1}

(5) Overall constants may be evaluated for the kinetic parameters (μ_{max}, K_S and k_d), and stoichiometric yield of biomass concentration (MLSS concentration) on substrate concentration (COD concentration) ($Y_{(X/S)}$).
(6) The influence of temperature on μ_{max} may be described by correcting for temperature:

$$k_T = k_{20} 1.04^{(T-20)} \tag{3}$$

and

$$\mu_{maxT} = Y_{(X/S)} k_T \tag{4}$$

where:

k_T: Maximum specific substrate utilization rate at T °C in d^{-1}
k_{20}: Maximum specific substrate utilization rate at 20 °C in d^{-1}
T: Mixed-liquor temperature in °C
$Y_{(X/S)}$: Synthesis yield co-efficient -

Next, the HRT and the SRT are respectively defined as:

$$\theta = \frac{V}{Q_f} \tag{5}$$

and

$$\theta_C = \frac{V}{Q_w} \tag{6}$$

where:

θ: HRT in d
V: MBR operational volume in m^3
θ_C: SRT in d

Finally, mass balances are as follows:

Mass balance on biomass (MLSS) concentration:

$$\frac{dX}{dt} = X\left(\mu - \frac{1}{\theta_C}\right) \tag{7}$$

where:

X: Biomass (MLSS) concentration in g L^{-1}
t: Time in d

which becomes

$$\mu = \frac{1}{\theta_C} \tag{8}$$

under steady state conditions.

Mass balance on substrate (COD) concentration:

$$\frac{dS}{dT} = \frac{(S_f - S)}{\theta} - \frac{\mu X}{Y_{(X/S)}} \quad (9)$$

where:

S_f: Feed substrate (Feed COD) concentration in g L^{-1}

which becomes

$$X = \frac{\theta_C Y_{(X/S)}(S_f - S)}{\theta} \quad (10)$$

or also

$$S = S_f - \frac{X\theta}{Y_{(X/S)}\theta_C} \quad (11)$$

at steady state.

The dynamic model equations: temperature corrected kinetics (Equations 2 to 4) and substrate and biomass mass balances (Equations 7 to 9) were solved simultaneously using a 4th order Runge-Kutta numerical integration routine for the differential equations, with a fixed step-length of 1 hour—this compares very favourably with sample intervals in the order of days to a week.

The feed flow rate (Q_f), the feed (influent) COD concentration (S_f), the MBR operating temperatures (T), and the respective HRT (θ) and SRT (θ_C) values as set by the required operating conditions were inputs to each MBR model. The discrete feed COD concentration and MBR operating temperature data were modelled using continuous interpolated spline functions, and the discrete values of HRT and SRT were modelled as continuous square wave functions. In this way, the varying model inputs could be described as continuous functions, and sampled accordingly in relation to the time steps of the numerical integration routine.

The MBR models were initialised with estimated values for the kinetic parameters (μ_{max}, K_S and k_d) and the stoichiometric yield ($Y_{(X/S)}$), and real values for the initial MBR biomass (X) and COD concentrations (S). As both MBR systems were seeded with the same biomass, and fed with the same waste water, the same parameters for kinetics and stoichiometry were used for each. A Gauss-Newton least squares routine was used to adjust the estimates of the kinetic and stoichiometric parameters until the errors between the dynamic model predictions for the X-value and S-value and the real pilot trial data were minimised.

MBR Energy Consumption Modelling

The Excel spreadsheet model of energy consumption was integrated with steady state mass balance equations (Equations 8, 10, 11) and the microbial kinetics and stoichiometry values estimated from the dynamic modelling, and used to predict the performance of each MBR system under different operating conditions. In particular, it was used to explore operating conditions which could lead to SED values equal to or lower than the 3 kWh m^{-3} of the full-sized AS plant. Although the target SED value appears to be relatively high for AS applications when compared to "typical" literature values of 0.2 to 0.4 kWh m^{-3} (Zhang et al., 2003; Liao et al., 2006), the full-sized AS plant in this study is operating with a higher-strength feed waste water and in extended aeration mode operation; hence, it requires higher levels of aeration than most equivalent plants in Europe where "typical" data is obtained. Clearly the treated water from the MBRs also has to be at least as good as that resulting from the AS plant. Finally, once identified, each set of operating conditions was compared to the operational data from the long-term MBR trials to ensure that the necessary membrane flux (net MPF) would lead to a stable long-term membrane performance. If not, the corresponding operating conditions were rejected.

The energy consumption model was operated by setting the SRT and HRT values, and then specifying the feed wastewater COD concentration. From this, the MLSS concentration in the MBRs, the required net MPF, which corresponds to the selected operating conditions of SRT and HRT, the resultant treated water COD concentration, and the SED value were calculated. The MBR operating temperature was standardised at 20 °C and the aeration rates for the membranes were the same as the long-term pilot trials and as per suppliers' guidelines (Table 1). Filtration in MBR_1 remained continuous, whereas filtration for MBR_2 was intermittent (9 min filtration, 1 min relaxation) as per the long-term pilot trials and in line with suppliers' guidelines. The model predictions were then compared to the operational data from the MBR pilot trials to test whether the required MPF was sustainable for any given set of tested operating conditions. The prediction of treated water quality was also compared to the Tunisian Standard for unrestricted human crop irrigation, namely a COD concentration of 90 mg L^{-1}.

Results and Discussion

MBR Energy Demand Analysis. It should be noted that data collected during the pilot trials are benchmark data collected under non-optimised conditions in terms of water throughput, but the energy comparison is nonetheless valid. It should also be remembered that these are small-scale pilot MBR systems which will naturally be much more sensitive to SED calculations given their small membrane areas and the loss of energy-economies of scale when compared to full-sized MBR installations. Additionally, they were not designed with optimised energy consumption in mind, rather to be mechanically robust in relation to demonstrating the technology in a new and untested environment. Table 2 summarises the energy consumption data collected during this aspect of the pilot trials. Comparing MBR_1 to MBR_2, the feed pump and air blower for MBR_1 consumed respectively more energy than the feed pump and air blowers in MBR_2. As the recorded power values for the MBR_1 components appeared to be quite high, the MBR_1 design may be modified by substituting the current components with alternative models that can operate at lower power values but deliver the same performance.

Both MBRs have control panels that provide a baseline energy demand when all other equipment (pumps and air blowers) is switched off. MBR_1 employs one pump for liquid pumping, whereas MBR_2 employs three pumps: a feed pump, a recirculation pump and a suction pump. With regard to aeration, MBR_1 operated with one air blower, whereas MBR_2 operated with three air blowers. All air blowers were operated continuously in this research.

MBR_1 consisted of one tank and hence both the biological treatment process and filtration took place simultaneously, and the gassing provided for both biomass maintenance and membrane scouring. Throughout MBR_1 operation, the air flow

Table 2—Measurement of the energy consumption rates per component and for each overall MBR system during the short-term experiments.

	Energy consumption rate (kWh d^{-1})		Percentage (%)	
Component	**MBR_1**	**MBR_2**	**MBR_1**	**MBR_2**
Control panel	***0.787***	***0.401***	***8.5***	***4.6***
Feed Pump	0.349	0.071	3.8	0.8
Recirculation pump	-	0.667	-	7.6
Suction pump	-	2.35	-	26.8
All pumps	***0.349***	***3.088***	***3.8***	***35.3***
Biological Aeration	-	1.063	-	12.1
Membrane Scouring	8.107	4.205	87.7	48
Total Gassing	***8.107***	***5.268***	***87.7***	***60.2***
All components	9.243	8.757	100	100

Note: Operating conditions were SRT = 15 d and HRT = 0.84 d for both MBRs.
Key: HRT: Hydraulic Residence Time, MBR: Membrane Bioreactor, MBRs: Membrane Bioreactors, MBR_1: Membrane Bioreactor 1, MBR_2: Membrane Bioreactor 2, SRT: Solids Residence Time.

rate of the MBR_1 air blower was kept constant and was equal to 4.2 m^3 h^{-1} as suggested by the manufacturer. MBR_2 comprised two tanks, a biological treatment tank and the membrane filtration tank. One air blower was used to provide air within the biological treatment tank for biomass maintenance, and two air blowers (one per membrane module) were used to provide gassing within the membrane filtration tank. The airflow rates of the MBR_2 air blowers were fixed by the manufacturer and could not be adjusted during trials. The airflow rate of each MBR_2 air blower was then equal to 6 m^3 h^{-1}.

From Table 2, it can be seen that power consumption for the control panels appears to be quite high for both MBR systems. This is attributed to the fact that control panels consume a similar amount of electricity irrespective of scale; therefore, full-scale MBR plants are likely to have much lower energy consumption for this component in relation to water throughput. It is, therefore, appropriate to ignore these figures when comparing the pilot-scale performance to the full-scale plant.

Table 2 shows that energy consumption for MBR_1 in relation to pumping accounted for about 4% of the total. This small proportion is attributed to the fact that the feed pump was operational only for a very short period of time over a day in comparison with the constant requirement for aeration. Similarly, energy consumed by the feed pump for MBR_2 was only 1% of the total consumption for the complete system. However, the overall energy consumption percentage for liquid pumping in MBR_2 was higher than for MBR_1 as the MBR_2 system required a recirculation pump and a filtration pump that were operational for quite long time periods. The filtration suction pump on its own consumed about 27% of the total demand for energy during the benchmarking, and it will consume more energy at higher net MPFs.

With respect to aeration (Table 2), the MBR_1 air blower consumed the highest amount of the overall energy, at a percentage slightly less than 90%, which is comparable to literature values for submerged gravity-driven MBRs (Gander et al., 2000). The MBR_2 air blowers also consumed the highest amount of energy for the system, but at a lower proportion of about 60%. This is expected given the greater requirement for pumping in MBR_2 compared to MBR_1. Although power consumption is likely to increase when higher airflow rates are applied, this aspect was not tested in this work as the selected airflow rates remained constant during operation of the MBRs. Gassing rates were maintained at the values indicated by the MBR suppliers throughout the trials.

In order to validate the energy consumption data collected during the short-term component-based energy-analysis experiments, a set of longer-term energy-analysis experiments were also carried out. In addition, energy readings were directly recorded from the mains electrical supply. The energy consumption values were normalised over a day and the corresponding energy consumption rates are shown in Table 3. It can be seen that the different energy-analysis experiments showed good consistency for MBR_1, whereas there was slightly more fluctuation for MBR_2. The errors between the energy consumption rates provided by the short-term experiments and the average energy consumption rates provided by the two different longer-term experiments is 1% for MBR_1 and 3.9% for MBR_2, in both cases this is considered negligible.

SED values were estimated by simply dividing an energy consumption rate value by the appropriate net membrane permeate flow rate. This data is summarised in Table 3. MBR_2 operated with lower SED values than MBR_1. However, when the energy data was collected, MBR_2 was operating at an unsustainable net MPF, as very soon afterwards there was a build-up of membrane fouling which necessitated membrane cleaning. On the other hand, MBR_1 was operating at a sustainable net MPF, as no significant membrane fouling occurred. This means that MBR_2 would actually have higher SED values if operated at a lower MPF in order to offset the fouling effect, whereas MBR_1 clearly had the potential to operate at higher membrane fluxes; thereby reducing the SED values.

Table 3—Overall energy consumption rates and SED values for each MBR system.

		Energy consumption rate (kWh d^{-1})		SED value (kWh m^{-3})	
Experiment		**MBR_1**	**MBR_2**	**MBR_1**	**MBR_2**
Short-term	In-line digital meters	9.243	8.757	5.339	3.738
Longer-term	In-line digital meters	9.225	9.134	5.329	3.889
	Mains power meters	9.447	9.082	5.475	3.887
	Average	9.336	9.108	5.402	3.888

Note: Operating conditions were SRT = 15 d and HRT = 0.84 d for both MBRs.
Key: HRT: Hydraulic Residence Time, MBR: Membrane Bioreactor, MBRs: Membrane Bioreactors, MBR_1: Membrane Bioreactor 1, MBR_2: Membrane Bioreactor 2, SED: Specific Energy Demand, SRT: Solids Residence Time.

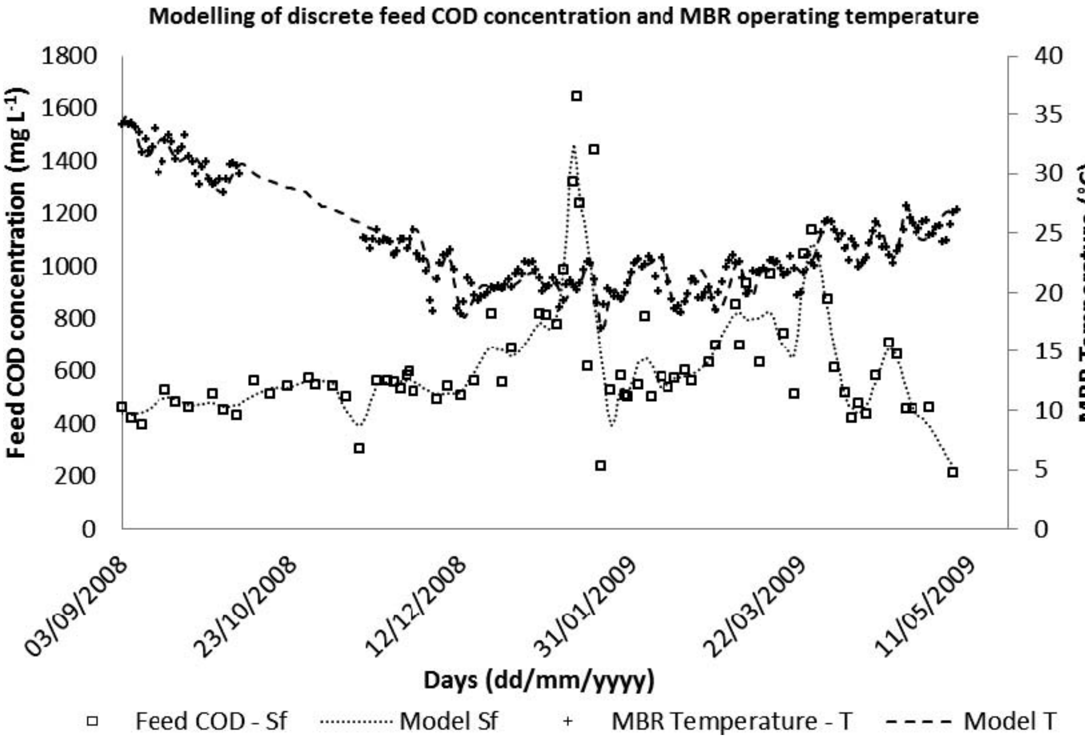


Figure 2—Continuous modelling of discrete feed COD concentration (S_f-value) and MBR operating temperature (T) data using interpolated spline functions.

It should be restated that these SED values are not presented as being optimal in any way, rather they are simply values corresponding to the operating conditions when the energy consumption data was collected. Operating conditions which resulted in the lowest SED values were explored using the MBR models developed subsequently.

MBR Dynamic Performance

Figure 2 indicates the good degree of fit achieved for the interpolated spline functions in comparison to the feed COD concentration and MBR operating temperatures. This is not surprising given the inherent flexibility of the approach. It should also be worth noting that there is considerable variation in the feed COD concentration, with most values being between 500 mg L^{-1} and 600 mg L^{-1}, but with a significant spike above 1,600 mg L^{-1} and some low values around 200 mg L^{-1}. There is also a fair variation in the MBR operating temperature due to seasonal variation in ambient temperature—the MBRs are operating in a range of temperature between a high of about 35 °C and a low of about 17 °C. Whilst large volume wastewater installations might expect to have much more stable temperature profiles with seasonal change, the small pilot-scale systems operated in Tunisia will obviously be more susceptible to such fluctuations. Clearly this will have a potentially significant impact on the kinetic constants of microbial growth; hence, the need for temperature normalisation in the modelling exercise. The dynamic performance data for MBR_1 and MBR_2 is presented in Figures 3a and 3b for the *X*-values and in Figures 4a and 4b for the *S*-values. In each case, the data from the pilot trial is presented in comparison to the results of the dynamic modelling analysis.

With respect to Figure 3a, the model slightly under-predicts the MLSS concentration in the first phase of operation of MBR_1 (HRT of 1.01 d and SRT of 15 d, MLSS of 4 g/L to 5 g/L), but the trend in general is good and fluctuations in the data are described well by the model. Although MBR_1 was not operated between 09/12/2008 and 23/01/2009, the model simulation was continued and it successfully covers the dynamic stage following start-up and the second phase of operation (HRT of 1.01 d, SRT of 30 d, MLSS of 9 g/L to 10 g/L). For MBR_2 (Figure 3b), the model predicts the experimental data with a good degree of accuracy, despite variations in the MBR inputs and operating conditions over time. The two "steady-states" (a. HRT of 1.01 d, SRT of 15 d, MLSS of 4–5 g/L; and b. HRT of 1.01 d, SRT of 30 d, MLSS of 9 to 10 g/L) are well described, as well as the dynamic period of operation between them. It should be noted that the model uses the same kinetic and yield parameters for both MBR systems throughout the whole period of the pilot trials, demonstrating the generally robust nature of the model, even though it is significantly simplified in comparison to more detailed alternatives.

With respect to Figures 4a and 4b, there is a lot of scatter in the raw data and the model does not predict the treated water quality (effluent COD concentration) very well during the first period of MBR_1 operation, but it does a reasonable job for the start-up and duration of the second period of operation. The under-prediction of treated water quality for MBR_1 at the lower MLSS concentration may reflect the fact that the MF Kubota system is designed to operate at higher than 10 g/L biomass concentrations, where there is greater potential for the development of a dynamic bio-layer on the surface of the membrane. There is plenty of evidence to suggest that this leads

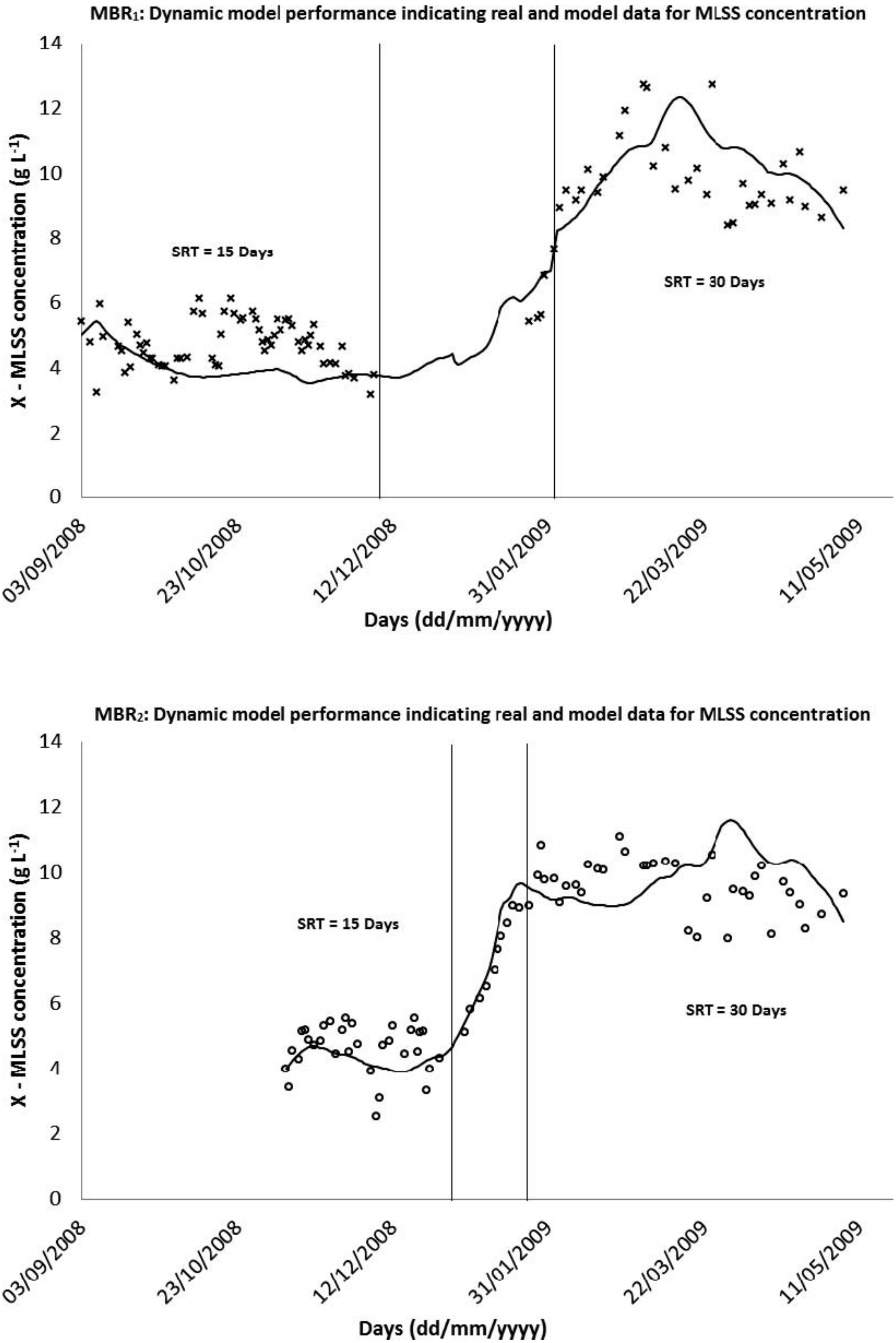
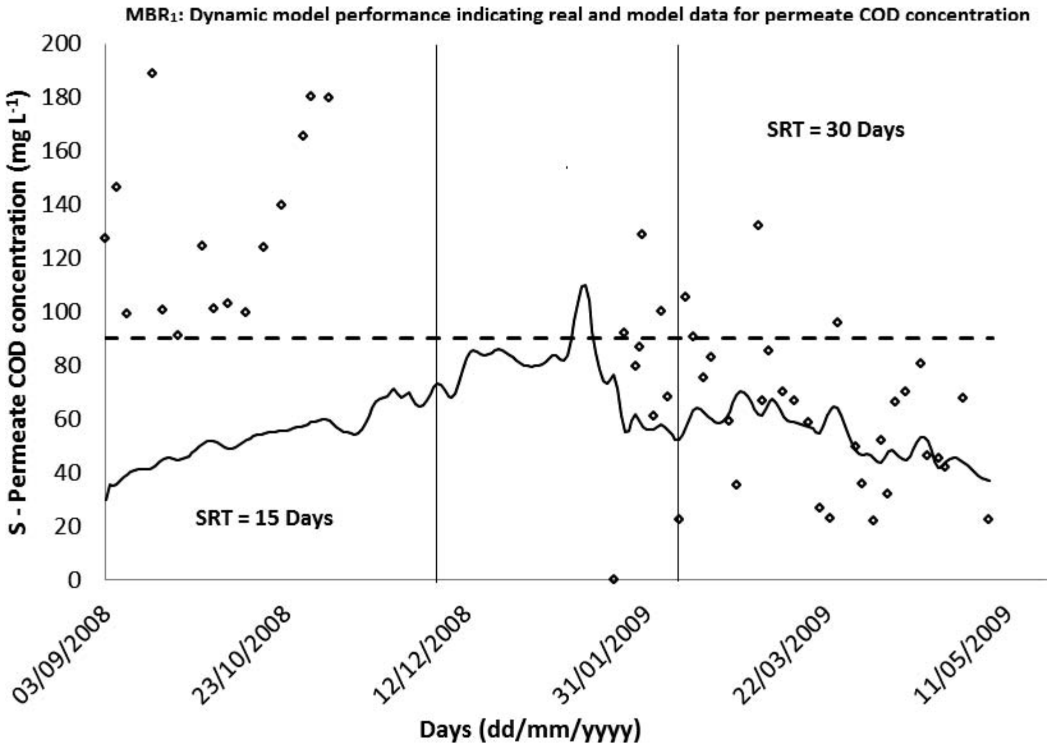


Figure 3—Dynamic model performance for MBR_1 (3a - top) and MBR_2 (3b - bottom) indicating real and model data for MLSS concentration (*X*-value).



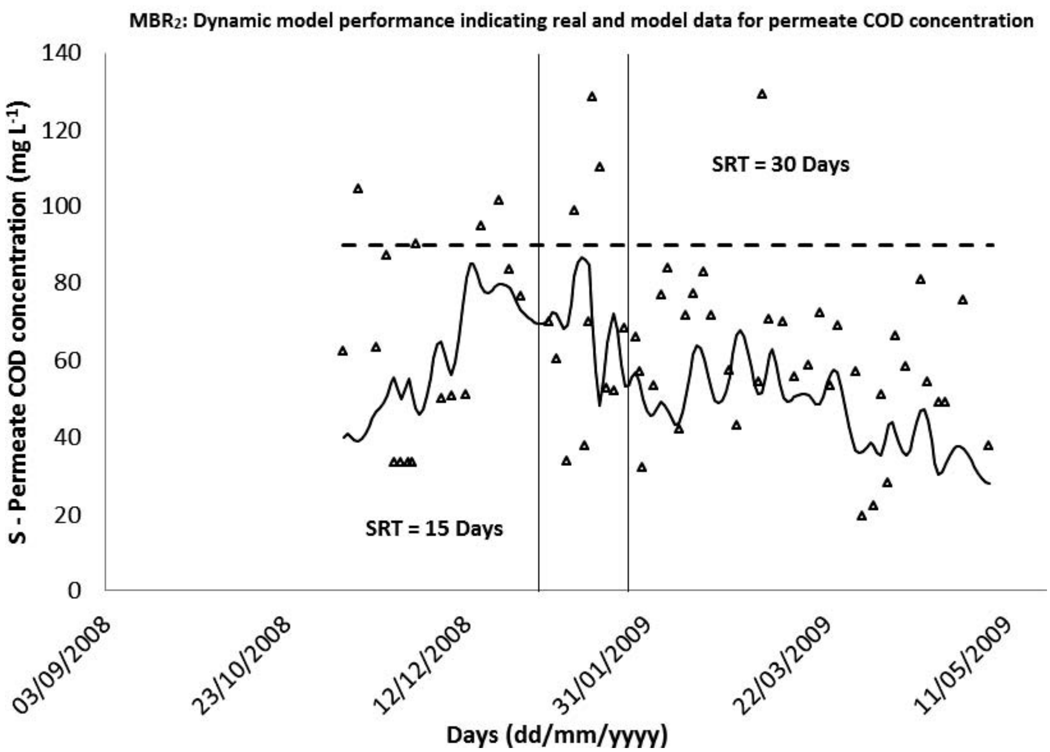


Figure 4—Dynamic model performance for MBR_1 (4a - top) and MBR_2 (4b - bottom) indicating real and model data for permeate COD concentration (*S*-value). Note: The horizontal dashed line represents the maximum COD concentration that can be used for unrestricted irrigation in Tunisia, 90 mg L^{-1}.

Table 4—Estimated stoichiometric and kinetic parameters for both MBR_1 and MBR_2 at a mixed-liquor temperature of 20 °C.

Parameter	Value	Unit
Maximum specific growth rate - μ_{max}	6	d^{-1}
Endogenous decay coefficient - k_d	0.075	d^{-1}
Substrate affinity constant (based on COD) - K_S	1,750	mg L^{-1}
Stoichiometric yield coefficient (based on COD) - $Y_{(X/S)}$	0.55	mg mg^{-1}

Key: COD: Chemical Oxygen Demand, MBR_1: Membrane Bioreactor 1, MBR_2: Membrane Bioreactor 2.

to greater membrane rejection of components, such as viruses and large molecules contributing to the feed COD content. As with MBR_1, the data for MBR_2 also shows a lot of scatter (Figure 4b). However, the model predicts the treated water quality well during the whole period of operation. Again, it should be noted that the same kinetic and yield parameters are used for both MBR systems throughout the whole time period of the pilot trials, demonstrating the robustness of the approach.

The kinetic and yield parameter values estimated from the dynamic modelling exercise are presented in Table 4. The estimated kinetic values for the maximum specific growth rate of the biomass, $\mu_{max} = 6\ d^{-1}$, and specific biomass decay rate, $k_d = 0.075\ d^{-1}$, are well within the expected range of numbers (Fan et al., 1999; Wen et al., 1999; Tchobanoglous et al., 2004). The value of the substrate affinity constant, $K_S = 1750$ mg/L, is high in comparison with values from "typical" treatment plants, which are processing conventional municipal wastewater streams. However, a high value of K_S should be expected given the fact that there are a number of industrial wastewater streams, including wastewater from olive oil processing, which are being received by the Sfax wastewater plant, and there is also slightly higher salinity in the wastewater. Both of these factors would lead to higher values of K_S due to the more recalcitrant industrial compounds and the presence of higher salinity in comparison to a "typical" municipal waste water stream. Based on COD concentration values, K_S-values of between 17833 mg/L and 23477 mg/L have been reported for waste water streams containing high amounts of oil and grease (Nakhla et al., 2006), and between 6220 and 6755 mg/L for the treatment of tannery waste waters (Durai et al., 2010). Whilst we do not suggest that the municipal waste water treated in the pilot MBR study in Sfax is anything like as high-strength as these reported cases, the presence of increased salinity, and some industrial wastes could easily lead to the K_S-values estimated in this work. The value of stoichiometric biomass yield on substrate, $Y_{(X/S)} = 0.55$, is within the range that might be expected (Tchobanoglous et al., 2004) for an extended aeration AS process, which is essentially the same operating regime as an MBR.

Overall, it is concluded that, although simple in approach, the dynamic modelling analysis has proved to be robust in the face of large variations in feed COD concentrations and MBR operating temperatures through the pilot trials. Also, the same set of kinetic and yield constants successfully described performance over the range of conditions tested for both MBR systems in terms of treated water quality and MLSS concentrations.

MBR Energy Consumption Performance

The energy consumption model was operated by setting the SRT and HRT values and specifying the feed COD concentration. From this, the SED values were estimated, along with the treated water COD concentration, MLSS concentrations and net MPFs. The *T*-value was normalised to 20 °C, and the airflow rates remained constant at the values recommended by the MBR suppliers. Filtration of MBR_1 remained continuous, whereas filtration of MBR_2 was intermittent with 9 min of filtration being followed by 1 min of membrane relaxation. This corresponded to the operating conditions that were tested during the long-term MBR trials, as well as being recommended by the membrane suppliers. The outcomes of the model were then compared to operational MBR data to test whether the required MPF was sustainable for any given set of tested operating conditions. Treated water quality was also compared to the Tunisian Standard for unrestricted irrigation, namely a COD concentration of 90 mg/L.

Initially, two SRTs were selected, namely 15 d and 30 d, and for each of these SRTs, the HRT was selected to range from 0.4 d to 1.1 d. The estimated SED values are plotted in Figure 5 and, from this, it can be seen that variation in the SRT from 15 d to 30 d did not significantly affect the SED values. For a fixed HRT, the SED values are of very similar values for either the short or the long SRT. As longer SRTs lead to higher MLSS concentrations, treated permeate of improved quality can be produced. However, the increase in the SRT is limited by the membrane performance, as high MLSS concentrations within the MBRs can lead to rapid formation of fouling layers around the membranes. On the other hand, variation in HRTs has a significant effect on the SED values; so, for a fixed SRT, an increase in the HRT is followed by a significant increase in the SED value. This is due to the fact that each time an increase in the HRT value occurs, a decrease in the net MPF is required. Consequently, less treated water is produced and the SED value will increase. It can be seen that for both MBRs, the SED values and net MPFs are inversely proportional.

It is also worth bearing in mind the operational guidelines provided by the MBR suppliers in each case. MBR_1, the system that was equipped with Kubota membranes, is designed to operate at MLSS concentrations typically in the range of 12 to 18 g/L; this is in order to promote the development of a bio-membrane layer on the surface of the MF Kubota membrane to enhance rejection, particularly of viruses. At lower MLSS concentrations, this bio-membrane layer is less likely to form, and rejection is reduced. The Kubota membranes are also generally operated with typical MPFs in the range of 5 to 25 L $m^{-2}\ h^{-1}$ (www.ovivowater.com, 2012).

Weise Water Systems, the supplier of MBR_2, recommend operation at MLSS concentrations in the range of 6 to 12 g/L and typical net MPFs are in the range of 15 to 30 L $m^{-2}\ h^{-1}$ (PURATREAT Project: Deliverable 3, 2007; www.weise-water-systems.com, 2012). The Weise Water UF membranes used in the MBR_2 system naturally have greater rejection than the Kubota MF membranes used in the MBR_1 system as the smaller pores of UF membranes reject organic matter that MF membranes fail to reject; so, the development of a bio-membrane layer is not necessary, and operation at lower MLSS

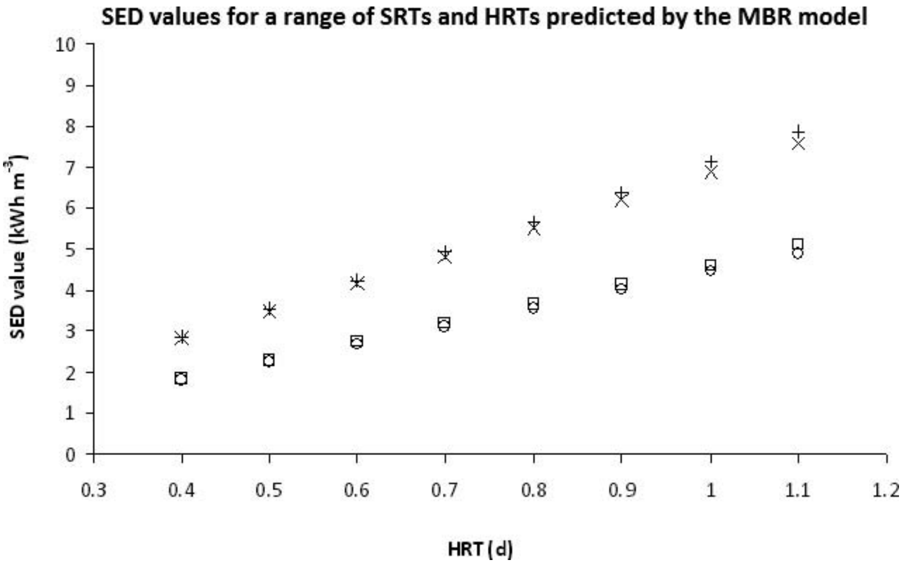


Figure 5—SED values for a range of SRTs and HRTs predicted by the MBR energy consumption model.
Symbols: + MBR_1 SED value for an SRT of 15 d, × MBR_1 SED value for an SRT of 30 d, □ MBR_2 SED value for an SRT of 15 d, ○ MBR_2 SED value for an SRT of 30 d Key: HRT: Hydraulic Residence Time, HRTs: Hydraulic Residence Times, MBR: Membrane Bioreactor, MBR_1: Membrane Bioreactor 1, MBR_2: Membrane Bioreactor 2, SRT: Solids Residence Time, SRTs: Solids Residence Times, SED: Specific Energy Demand

concentrations is possible. On the other hand, the spacing between the MBR_2 membrane panels is smaller than that between the MBR_1 membranes, namely a 5 mm gap for MBR_2 compared to 7 mm for MBR_1. This means that there is greater potential for channel clogging/blockage with the MBR_2 membranes at higher MLSS concentrations, and hence a lower value is recommended for sustainable operation (PURATREAT Project: Deliverable 3, 2007).

The MBR energy consumption model was evaluated for an SRT of 30 d and HRTs ranging from 0.4 d to 1.1 d at a selected MBR operating temperature of 20 °C—the results of the modelling exercise are presented in Figure 6. The SED values and the net MPFs are plotted against the MLSS concentration which resulted from the selected operating conditions. This allowed easy comparison with operational data from the MBRs to identify those model predictions which corresponded to sustainable MPF and appropriate water quality (effluent COD concentration) in reality.

From Figure 6, it can be concluded that MBR_1 was generally unable to operate at SED values lower than 3 kWh m^{-2}, even though the model was tested over a wide range of MLSS concentrations and net MPFs. The only condition that leads to a SED value lower than 3 kWh m^{-3} was with a low HRT of 0.4 d and corresponding MLSS concentration of 24.7 g/L and net MPF of 25.29 L m^{-2} h^{-1}. This is highly unlikely to lead to stable long-term membrane performance given the fact that during the long-term operation of MBR_1 in these trials, it could only reach a sustainable net MPF of 13.77 L m^{-2} h^{-1} at a mixed-liquor temperature of 30 °C and an average MLSS concentration of 9.26 g/L. However, in relation to the treated water quality, the predicted effluent COD concentration of 32 mg/L was acceptable as it was below the required maximum value of 90 mg/L.

From Figure 6, it can be seen that MBR_2 was able to operate at SED values lower than 3 kWh m^{-3}, but only when the HRT was 0.6 d or less. At an HRT of 0.6 d, the SED value was 2.69 kWh m^{-3}, with an acceptable treated water COD concentration of 32 mg/L. However, even though these values are in line with targets and better than the performance of the full-sized AS plant, the corresponding combinations of MLSS concentrations and net MPFs will lead to unsustainable membrane performance as both had reached high values of 16.72 g/L and 19.66 L m^{-2} h^{-1} respectively. According to the long-term MBR_2 trials, these conditions would lead to rapid membrane fouling and this outcome also supports the operating guidelines supplied by the manufacturer. During the long-term MBR_2 operation, it was concluded that the maximum net MPF that can be sustained was about 12.81 L m^{-2} h^{-1} at an average MLSS concentration of 9.21 g/L, an MBR tank airflow rate of 12 m^3 h^{-1} and at a mixed-liquor temperature of 24 °C. So, although this set of operating conditions is theoretically interesting, in practice, it could not be achieved with this MBR.

MBR_1 Upgrade Scenario

As noted earlier from the energy analysis, some of the components of MBR_1 appear to be oversized. If these components were to be replaced with alternatives which supplied the same performance at lower energy consumption, the SED value could be lowered. The model was therefore used to predict SED values for a hypothetical MBR_1, whose design has been improved by replacing the high energy-consuming feed pump and air blower by devices with lower energy-consumption. A feed pump similar to that of MBR_2 can be utilised for MBR_1, and the MBR_1 blower can be replaced by a slightly larger version of the unit used in MBR_2 (www.airmac.com.tw, 2012). In both cases, the performance will match the existing equipment, but the necessary energy consumption will be reduced significantly.

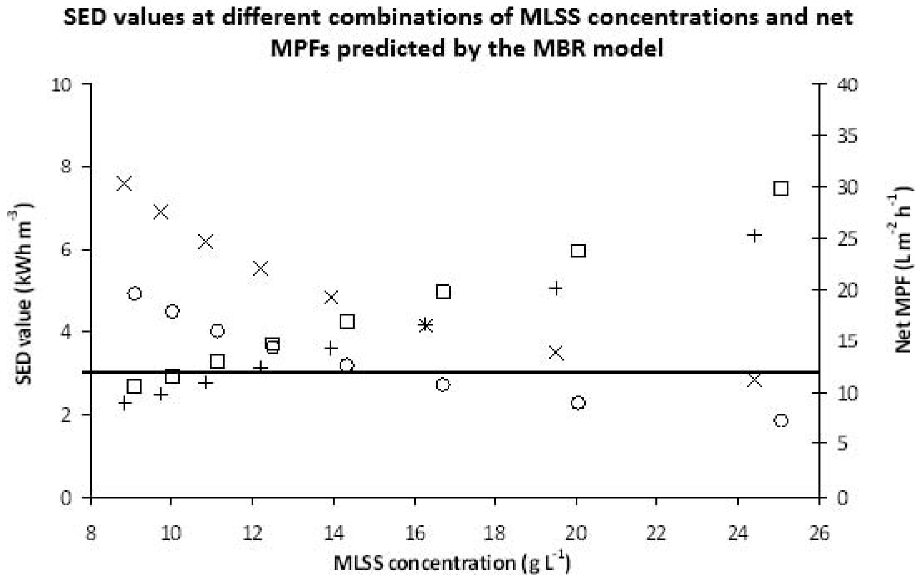


Figure 6—SED values for MBR_1 and MBR_2 at different combinations of MLSS concentration and net MPFs predicted by the MBR model, for an SRT of 30 d and HRTs ranging from 0.4 d to 1.1 d.
Symbols: — Target SED value (corresponding to the full sized AS plant), × MBR_1 SED value, ○ MBR_2 SED value, + MBR_1 net MPF, □ MBR_2 net MPF Key: AS: Activated Sludge, HRTs: Hydraulic Residence Times, MBR: Membrane Bioreactor, MBR_1: Membrane Bioreactor 1, MBR_2: Membrane Bioreactor 2, MLSS: Mixed-liquor Suspended Solids, MPF: Membrane Permeate Flux, MPFs: Membrane Permeate Fluxes, SRT: Solids Residence Time, SED: Specific Energy Demand

The model was finally used again to test the MBR_1 upgrade scenario and establish whether the target energy consumption could be achieved. The SRT was again set to 30 d and HRTs ranging from 0.4 d to 1.1 d were tested. The mixed-liquor temperature was normalised to 20 °C, and the air flow rate was set to 4.2 m^3 h^{-1} as per the supplier's recommendations. For all HRT values of less than 0.9 d, the SED values were lower than the 3 kWh m^{-3} target. For an SRT of 30 d and an HRT of 0.9 d, the MLSS concentration was predicted to be 15.44 g/L, the net MPF was 11.05 L m^{-2} h^{-1}, the treated water COD value was acceptable at 32 mg/L, and the SED value almost 3 kWh m^{-3}. The long-term MBR trials, together with the information provided by the MBR_1 suppliers, demonstrate that this combination of net MPF and MLSS concentration may be able to lead to sustainable membrane operation, and the predicted treated water quality and SED value are better than either the targets or what is currently possible with the existing full-sized AS plant.

It is finally interesting to predict the combination of the MLSS concentration and the net MPF which correspond to a SED value of 3 kWh m^{-3} as achieved by the AS plant. For an SRT of 30 d, the HRT was adjusted until the predicted SED corresponded to 3 kWh m^{-3}. The HRT value at this point was 0.88 d with the mixed-liquor temperature and the air flow rate at standard values, *i.e.* 20 °C and at 4.2 m^3 h^{-1} respectively. Based on these operating conditions, the energy consumption model predicted an MLSS concentration of 15.82 g/L and a net MPF of 11.34 L m^{-2} h^{-1}, together with an acceptable effluent COD concentration. In comparison with real data collected during the long-term operation of MBR_1, it can be said that the proposed modification to MBR_1 may well satisfy the key objectives of this work in comparison to the full-sized AS system. It outperforms the AS plant on the basis of treated water quality, provides stable long-term membrane performance, and can operate at SED values equal to or lower than 3 kWh m^{-3}. Marginal extrapolation of this model, coupled with cross-checking of performance data from the long-term MBR_1 trials, will indicate that sustainable MPFs and appropriate treated water are maintained at SED values down to the range of 1 to 3 kWh m^{-3}. In full-sized submerged MBRs, energy consumption rates appear to be lower than 1 kWh m^{-3} (Ndinisa et al., 2006); however, the literature reports a very wide range *i.e.* between 0.2 kWh m^{-3} and 4.0 kWh m^{-3} (Howell et al., 2004; Liao et al., 2006; Verrecht et al., 2010). Given the small scale of the MBRs, and the inherent loss of economies of scale with respect to energy consumption, and the opportunity for decentralised municipal waste water treatment, these values are proposed as being an acceptable proof of concept and a starting point for further refinement.

Conclusions

Two pilot MBR systems have been tested on Tunisia in order to evaluate their potential for decentralised treatment of municipal wastewater contaminated at times with some industrial impurities. Key operational parameters, such as HRT and SRT were varied during long-term trials, and the resultant MLSS concentration, treated water COD concentration, and SED values were measured.

In both MBR systems, the most-energy consuming components were the air blowers, corresponding to 88% of the total energy consumed by MBR_1, and 60% of the total energy consumed by MBR_2. This is as expected in relation to operation of submerged MBR systems. Liquid pumping consumed 4% of the total energy in MBR_1 and 35% of the total in MBR_2, the difference being largely due to the additional recirculation and permeate pumps required to operate MBR_2.

The dynamic MBR model used in this work was shown to be robust in the face of variations in feed wastewater concentration, and also in the operating temperature of the MBR systems. The same kinetic and stoichiometric parameters were used to acceptably predict the behaviour of the two MBR systems under different SRTs and HRTs, despite these variations. The model was then extended to include predictions of specific energy consumption under different operating conditions.

After testing the model through a range of SRT and HRT values corresponding to the operational MBR trials, it was concluded that it was impossible to ensure stable membrane performance at SED values equal to or lower than 3 kWh m^{-3} for either MBR system. However, a modified design of the MBR_1 system, where the oversized pump and blower were replaced by less energy-consuming equivalents, could lead to SED values lower than 3 kWh m^{-3} and at the same time producing treated permeate with a COD concentration lower than the 90 mg/L target, at a sustainable long-term membrane performance.

The MBRs were operated with SED values similar to or less than the full-sized AS plant, but produced treated water of greater quality. Water leaving the AS plant requires sand filtration followed by UV (ultra-violet) disinfection for removal of pathogens before it can be used for unrestricted irrigation in Tunisia, adding unsustainable costs to the process. However, the treated water from the MBR systems was of suitable quality for direct use in unrestricted irrigation, at an acceptable energy cost. The microbial quality tests that were accomplished both for the influent and for the permeate showed that, even though a wide range of micro-organisms was always present in the influent waste water, the MBR effluent was always completely pathogen-free. In conclusion, this work demonstrates that small-scale pilot MBR systems can be operated successfully in the North African context, we believe for the first time, with respect to municipal wastewater treatment. The potential for decentralised treatment systems for water re-use has also been demonstrated.

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