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Membrane bioreactor for domestic wastewater treatment: energetic assessment

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ABSTRACT

Increasing interest in sustainable wastewater treatment has led to a fundamental change in treatment system operation. A key aspect of improving overall sustainability is the potential for direct wastewater effluent reuse. However, membrane bioreactors (MBR) have been identified as an attractive option for producing high quality and nutrient-rich effluents for municipal and domestic wastewater treatment. Currently, with the evolution of wastewater treatment projects in Morocco, the MBR process can be used as a technology treating different types of wastewater and to produce effluent with suitable quality for reuse. However, the energetic consumption of this process is a great concern, which can limit the development and implementation of this technology. In this investigation, the electric energy consumption of an ultrafiltration membrane bioreactor process in domestic wastewater treatment is evaluated and compared to some MBR installations based on literature review. Energy requirements of the MBR are linked to operational parameters and reactor performance. The analysis of energy consumption shows that the biological aeration and membrane filtration are more energy consuming than the other components listed as feed and recirculation pumps. Biological aeration needs 53% of the overall energetic consumption and the specific energy consumption for membrane filtration is about 25%. However, aeration is a major energy consumer, often exceeding 50% share of total energy consumption. The best results obtained on the MBR system (pressure p = 1.15 bar), hydraulic retention time (15 h) showed removal efficiencies up to 90% in terms of organic compounds removal, 100% in terms of suspended solids presence and up to 80% reduction of total nitrogen and total phosphorus. The effluent from this MBR process could be considered as qualified for municipal reuse in Morocco, showing its potential application in the future.

Keywords: Membrane bioreactor; Ultrafiltration; Wastewater treatment; Energy consumption

1. Introduction

Water is one of the most natural and essential needs for life resource [1]. About 97% of the world's water resources appears as salt water in seas and oceans. Only 3% can potentially be used for human needs and a large part of this freshwater is not directly available to humans. Therefore, the protection of the raw material water is one of the main tasks of today and of tomorrow [2]. However, increasing interest in improvement of treatment effectiveness and sustainable wastewater treatment has led to a fundamental change in treatment systems operation. A key aspect of improving overall sustainability is the potential for direct wastewater effluent reuse [3]. One of the new technologies that have gained attention is that of membrane bioreactor (MBR) technology, integrating conventional biological treatment and membrane filtration. MBR technology allows high sludge age, low hydraulic retention time and a higher

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biomass concentration than the conventional activated sludge process (ASP) treatment [4].

From a global perspective a growing confidence in MBR technology is demonstrated by the exponential increase in the cumulative MBR installed capacity. With new factors coming into play, MBR technology is now regarded as mature and various authors denominate MBR as the best available technology for wastewater treatment [5]. Currently, with the evolution of wastewater treatment projects in Morocco, the MBR process can be used as a technology to treat different types of wastewater and to produce effluent with suitable quality for reuse [6]. However, MBR technology has some advantages such as a superior treated effluent quality and low plant footprint [7,8], but an important disadvantage is the high energy demand [9,10]. Specific energy consumption (SEC) is the energy consumed for treatment of a unit volume of wastewater. It is commonly expressed in units of kWh/m^3 [10]. The SEC of whole MBR wastewater plants was reported to be about 0.5–8 kWh/m^3, quite a broad span, depending on the influent characteristics and plant capacities. The energy requirement of the first tubular side-stream MBR installations have been reported to be in the range of 2.0 and 8.0 kWh/m^3 [11]. This high energy demand, mainly due to energy intensive cross-flow pumping of the liquid and high aeration requirement due to the oxygen consumption for the respiration of the large amount of biomass present undergoing aerobic. This endogenous respiration of the bacterial cells allows the oxidation of the carbonaceous organic matter and oxidation of the organic carbon to supply energy for bacterial synthesis [12].

However, development in MBR technology resulted in an energy demand reduction from about 5.0 kWh/m^3, needed for the first side-stream MBR, to 1.0 kWh/m^3 [13]. Stephenson et al. [14], reported that the energy consumption rates of 2 to 10 kWh/m^3 for sidestream operation and 0.2 to 0.4 kWh/m^3 for submerged operation. In the recent MBR processes, energy consumption is typically below 1 kWh/m^3 of produced permeate. Both in submerged and side-stream MBRs the abovementioned energy components are intended to remove or minimize fouling. Membrane fouling is closely related to energy consumption; hence, reducing membrane fouling in MBR while keeping energy consumption as low as possible is the main focus of MBR [15,16]. Therefore, the major cause of high energy consumption in MBR technology is the prevention and minimization of membrane fouling [17,18]. However, energy consumption is a driving factor for the operational costs of membrane bioreactor plants [5]. It becomes important to understand the best way of including these new technologies at the aim of having a low energy consumption. To research the specific energy requirements of MBR systems and elucidate where possible future energy consumption reduction can be achieved, extensive research on the specific energy consumption in several MBR plants was performed [18].

In the present study, the electric energy consumption of an ultrafiltration (UF) MBR process in domestic wastewater treatment is evaluated and compared to some MBR installations based on literature review. The performance of the MBR pilot is evaluated in environmental and energy demand terms based on major performance indicators as proposed by Benedetti et al. [19] and Yang et al. [20]: Effluent concentration of pollutants (mg/L), removal efficiencies of pollutants expressed as % of incoming load, and energy consumption per volume of treated wastewater (kWh/m^3).

2. Materials and methods

2.1. MBR configuration, inoculation and operational parameters

Experiments were performed in a lab-scale MBR pilot system using UF membrane. A schematic diagram of the experimental facility is shown in Fig. 1, mainly consisted it of three components: anoxic tank, aeration tank; UF membrane module and for chemical membrane cleaning a cleaning tank. The detailed design and operating parameters are shown in Table 1. The detailed operation of the MBR setup has been explained elsewhere [21].

The seed sludge was obtained from an activated sludge taken from a wastewater treatment plant (WWTP) situated in National Office of Electricity and Drinking Water (ONEE) in Rabat, Morocco. During the start-up period, the bioreactor was operated for 32 d.

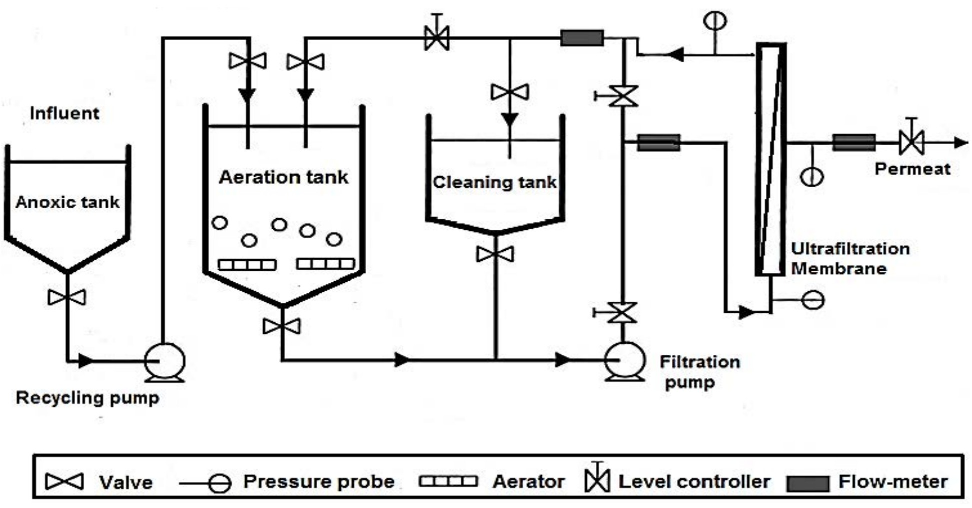

Fig. 1. Flow diagram of the experimental ultrafiltration membrane bioreactor (MBR).

The bioreactor was operated continuously to assess the long term treatment efficiency of the MBR at psychrophilic temperature (15°C–25°C) [22]. Because, in addition to the heat of biological reaction, pumping operations in MBRs can provide additional benefit in raising the reactor temperature to both increase biotreatment efficacy and reduce liquid viscosity and the energy input of crossflow ultrafiltration could also raise temperatures in MBRs to the optimum.

2.2. Influent characteristics

The influent used in the study is the domestic wastewater. Wastewater composition and characteristic are listed in Table 2, are within the standard limits of World Health Organization (WHO) and US-EPA [23]. However, total suspended solids (TSS) (397–457 mg/L), biological oxygen demand (BOD_5) (275–470 mg/L), and chemical oxygen demand (COD) (527–647 mg/L) are considerably deviated from their prescribed limits, indicating the high level of contamination. Pollution loads are assumed to be all of domestic origin. As shown, the wastewater characteristics can represent the medium-strength urban wastewater seen in Morocco and in most cities around the world [24,25]. Furthermore, these values exceed the specific limit values of Moroccan domestic discharge and the reuse standards, hence the necessity for wastewater treatment [21].

Table 1
Main characteristics and operating parameters of the MBR system

Aeration tank volume	40 L
Hydraulic retention time	15 h
pH	6.5–8
Temperature in aeration tank	15°C–25°C
Aeration rate	300 N L^{-1}
Dissolved oxygen	3.5–5.5 mg/L
MLSS	7–15 g/L
Membrane module material	Ceramic
Membrane length	1,178 cm
Diameter of the channels	6 mm
Membrane area	0.45 m^2
Pore size	0.035 μm
Maximum transmembrane pressure	1.15 bar

MLSS: Mixed liquor suspended solids.

2.3. Sampling and analysis

The influent, mixed liquor and permeate samples are collected and analyzed periodically. All sample analyses including COD, BOD_5, TSS, nutrients (N and P), and metal ions concentrations are conducted following standard methods [26–28]. Also, the disinfectant efficacy of MBR processes is evaluated; analyses of total coliforms are carried out in the bacteriology laboratory using the filter membrane method [29].

2.4. Energy consumption

The energy consumption data, reported as kWh, are based on the electric power consumed by the MBR pilot. The SEC data are reported as specific electricity consumption per volume of treated wastewater and expressed as kWh/m^3 [30].

Power requirements in the MBR system are divided into five parts. They are energy consumption due to oxygen supply in the biological aeration tank, the feed and recirculation pumps in the system, the filtration pumps (membrane module) and the energy lost by the rest of MBR. However, total energy consumption is the sum of the five parts and symbolized as E (kW), can be calculated by the following formula [31]:

$$E = \left(E_1 + E_2 + E_3 + E_4 + E_5\right) / Q_p / 3{,}600 \quad (1)$$

$$E_1 = Q_p \times W \times 3{,}600 = Q_p \times 0.28 \times 3{,}600 = 1{,}008 Q_p \quad (2)$$

where E_1 is the energy consumption by oxygen supply in aeration tank (kW), Q_p is the permeate flow rate (m^3/s), and W is the average energy consumption for aeration, whose value is set as 0.28 kWh/m^3 based on a report by Dutch wastewater treatment plants [32].

Table 2
Quality of domestic wastewater

Parameter	Influent concentration	Discharge standards[a]	Reuse standards[b]
Temperature, °C	21.5–27	<30	35
pH value	7.5–8.5	5.5–9.5	8.4
Electric conductivity (E), μS/cm	1,220–1,700	2,700	1,000
COD, mg/L	527–647	250	100
BOD_5, mg/L	275–470	120	20
TSS, mg/L	397–457	150	<50
TN, mg/L	53–71	40	<5
TP, mg/L	12–17	15	–

[a]Moroccan pollution standards – Specific limits for domestic discharge.
[b]This is the maximum permissible values according to Directive FAO and Water Reuse Standard for Irrigation, Land Watering, Morocco.

$$E_2 = Q_2 \times (P_1 - P_2) \times 100 + Q_p \times \left[\frac{(P_1 + P_2)}{2} - P_3 \right] \times 100 \quad (3)$$

where E_2 is the energy consumption by membrane filtration (kW), Q_2 is recirculating flow rate (m^3/s), Q_p is permeate flow rate (m^3/s), P_1, P_2 and P_3 are inlet membrane module pressure, outlet membrane module pressure and permeate pressure respectively (bar).

$$E_3 = \left(\frac{1}{\eta} - 1 \right) \times \gamma \times Q_3 \times H_t \quad (4)$$

where E_3 is energy consumption by pump (kW), g is pump efficiency, usually ranges from 60% to 85%, Q_3 is pump capacity (m^3/s), γ is specific weight of water (kN/m^3), and H_t is total dynamic head (m).

$$E_4 = \gamma \times Q_4 \times H \quad (5)$$

where E_4 is energy consumption by pipe system (kW), γ is the same as above, Q_4 is flow rate inside pipe (m^3/s), and H is hydraulic head dropped in the pipe (m).

$$E_5 = \gamma \times V^2 (2g)^{-1} Q_5 \quad (6)$$

where E_5 is velocity energy lost (kW), γ is the same as above, V is velocity of returned mixed liquor to the bioreactor (m/s), Q_5 is flow rate of returned mixed liquor (m^3/s), and g is acceleration due to gravity (9.81 m/s^2).

3. Results and discussion

3.1. MBR performance and effluent quality

The summary of overall performance of the investigated MBR, in terms of pollutants removal efficiency, with minimal, average and maximal values, is presented in Figs. 2 and 3.

Good removal efficiencies of COD, BOD and total nitrogen (TN) are achieved in MBR process. MBR removed COD to about 27 mg/L with removal efficiency of 95.4%. In a study by Valderram et al. [33], with a MBR process, total COD removal was 97% on average. BOD is removed far below the 15 mg/L requirement with efficiencies of about 96.7%. This indicator used to measure the biochemical oxygen demand for the natural destruction of the organic matter present in water [28]. TSS is removed with 99.5% efficiency to concentrations of about 2.0 mg/L.

The average value of TN (N-Total) achieved by MBR is 3.3 mg/L. Nonetheless, phosphorus removal of 90% reaching total phosphorus (P-Total) concentrations of 1.5 mg/L is attained in MBR.This removal of nitrogen and phosphorus in MBR could be beneficial if the treated effluent is intended to be used for irrigation purpose. Chen et al. [34] suggested that the forward osmosis membrane process could provide another perspective to resolve this challenge and it can almost totally reject N and P contaminants. Much researches had confirmed that MBR is a highly viable wastewater treatment technology regarding nitrification–denitrification and phosphorus removal compared to ASP. With optimized design and operating parameters it warrants high effluent quality in terms of nitrate and phosphorus present in wastewater [35–37].

Regarding the electric conductivity of the MBR permeate, this parameter has been reduced with an average of 35%. The averages are close to Moroccan water quality standards for irrigation [38].

Table 3 summarizes the mean values of heavy metals and total coliforms removal. For the study of heavy metals, analyses of five main heavy metals (zinc, iron, copper, plumb and nickel) are carried out. The results show that the concentrations of the heavy metals present in MBR permeate has decreased and comply with the irrigation reuse standards. Moreover, for the MBR the UF membranes are able to retain TSS. Consequently, the metal ions attached

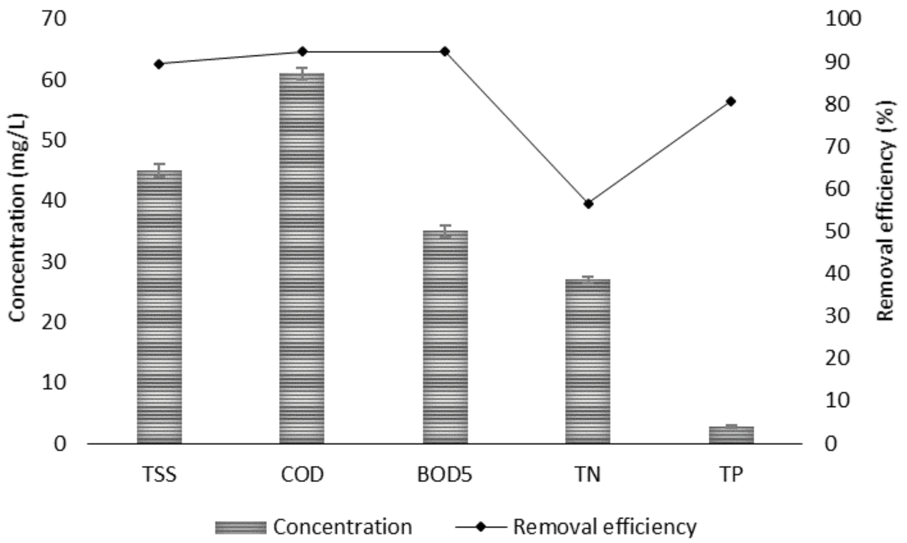

Fig. 2. Concentration values and removal efficiencies rate of pollutants after biological treatment.

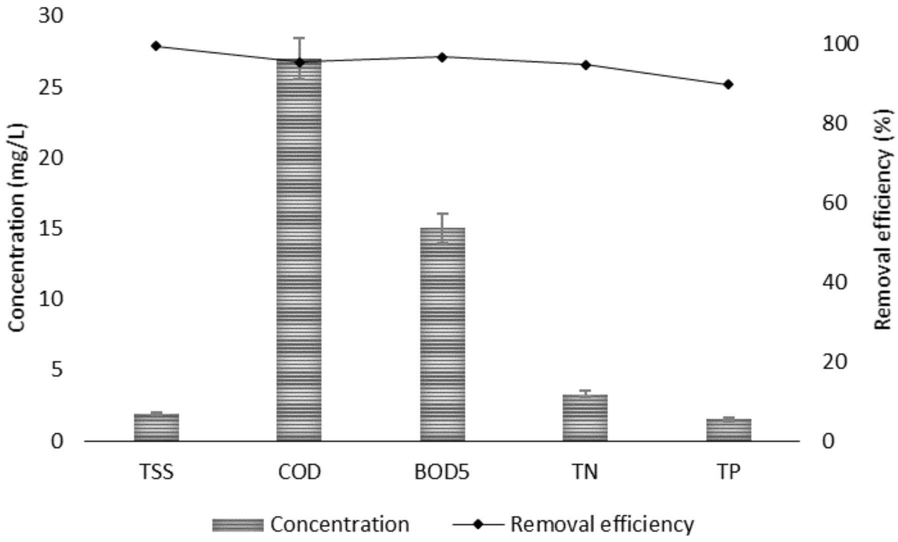

Fig. 3. Concentration values and removal efficiencies rate of pollutants after membrane filtration (UF).

Table 3
Heavy metals and bacteria removal

Parameter	Influent	Standard deviation	MBR permeate	Standard deviation	Discharge standards	Reuse standards[a]
Iron (Fe), mg/L	2.5	0.05	2.5	0.1	5	5.0
Copper (Cu), mg/L	0.2	0.03	0.1	0.05	2	0.2
Zinc (Zn), mg/L	1.1	0.05	0.5	0.1	5	2.0
Plumb (Pb), mg/L	0.1	0.05	0.1	0.06	1	5.0
Nickel (Ni), mg/L	0.2	0.06	0.1	0.07	5	0.2
Faecal coliforms, $\log_{10}$ CFU/100 mL	>10	–	0.5	–	–	3.69

[a]This is the maximum permissible value according to Directive FAO and Water Reuse Standard for Irrigation, Land Watering, Morocco.

to sludge flocs are effectively retained by UF membranes. In one study, Heo et al. [39] have reported that UF membranes can remove a number of heavy metals. Besides, these results obtained are consistent with the values of the Food and Agriculture Organization of the United Nations (FAO) and EPA [40], which indicate the maximum concentration of trace elements in reuse water for irrigation [41]. Removal of toxic metals makes treated wastewater reliable for reuse and contributes to water sustainability. However, membrane processes such as UF, nanofiltration (NF) and reverse osmosis (RO) have proven their competitiveness in removal of metals from wastewater because of their low energy requirement, small volume of concentrate, and high selectivity. The removal of toxic metals makes wastewater safe for reuse and contributes to water sustainability [42].

Concerning bacteriological analysis, the faecal coliforms, which are generally used as indicators to determine the degree of disinfection [40] are also monitored during the experiment. According to the results it can be observed that the concentration is lower than 1 $\log_{10}$ CFU/100 mL, while in the influent the concentration is upper to 10 $\log_{10}$ CFU/mL. The same result is reported at the level of an effluent treated by MBR in Morocco [43]. Indeed, the small size of the pores of the UF membrane makes it possible to block all the bacterial species. The results of this study indicate that the MBR system can achieve better microbial removal [22]. Also, these results confirm those obtained by Baudart et al. [44] in a similar study for MBR wastewater treatment, which found that the use of membrane allows effective removal of pathogenic indicators (total and faecal coliforms).

3.2. Total and specific energy consumption

The study for the SEC determination of the MBR process is carried out under the optimal operational conditions previously determined. To show how each element of the MBR system contributes to the total functional costs, five main consumer components are analyzed and presented in Figs. 4 and 5. Energy demand of the feed pump, energy consumption demand of the biological aeration compressor and bubble diffusers, recirculation pump power consumption demand, recorded demand for the operation of the filter pump (high pressure pump) and other energy consuming elements of the MBR.

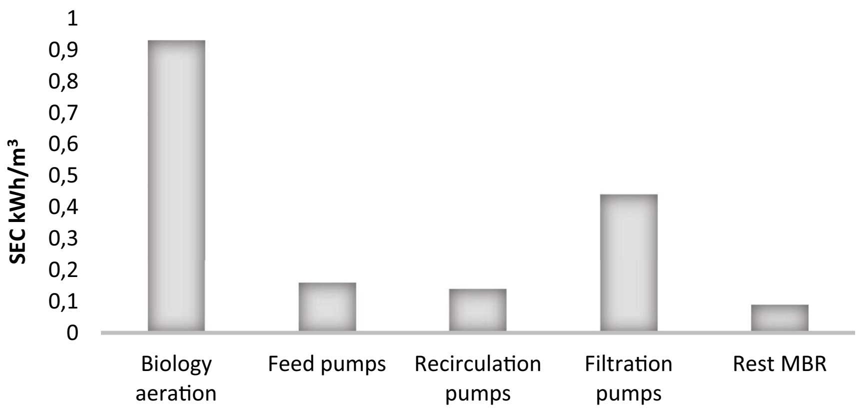

Fig. 4. SEC distribution of MBR components.

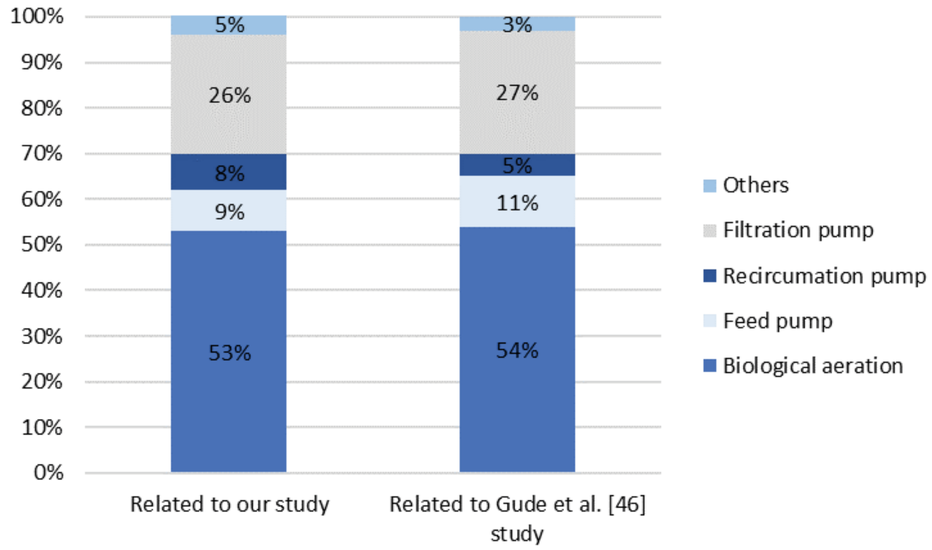

Fig. 5. Energy consumption distribution of MBR equipment for MBR wastewater treatment is related to our study and Gude [46] study.

The results show that the biological aeration process contributes more than 50% of the total energy demand, while the second-biggest consumer is the membrane filtration pump with a consumption rate of 0.44 kWh/m^3 or a rate of 25% of total energy used. The feed pump which pumps wastewater from the reservoir to the anoxic tank consumes about 0.16 kWh/m^3 or a rate of 9%. And the recirculation pump which pumps the wastewater from the anoxic basin to the biological basin uses 0.14 kWh/m^3 or a rate of 8%. The remainder (5%) represents the energy consumed by other installed equipment [45]. The same results were reported by Gude [46], (Fig. 5). They found that the main energy consumer of MBR systems was the aeration with a percentage amount of 54.1%, also confirmed by Gu et al. (60%) [47]. Similarly, in wastewater treatment plants, the aeration equipment consumes anywhere between 50% and 75% of the total energy consumption from large to small plants respectively. However, biological aeration was identified as the main energy consumer among MBR. It has the greatest share and therefore the greatest potential for energy efficiency improvements [46]. Several studies reported that the energy consumption rates of external MBR (eMBR) ranged between 2–10 kWh/m^3 and 0.2–0.4 kWh/m^3 for submerged (sMBR), operation was required for aeration [48].

In this study, the total energy consumption calculated of the MBR is 1.75 kWh/m^3. Krzeminski et al. [49] applied MBR technology for wastewater treatment and they found that the SEC of this technology varies between 0.87 and 1.05 kWh/m^3. In the same study, the biological aeration demand was evaluated to 53% of the total MBR specific energy. In similar studies on MBR, Rieger et al. [50] found that the biological aeration rate reaches 60% of the total energy consumption. For their part, Radjenović et al. [51] have shown that the biological aeration is the biggest contributor of energy to the MBR system, due to the oxygen demand for biological degradation of organic matter. In many studies, aeration was identified as the main energy consumer in MBR processes. Most of the published results dealt with lab-scale tests and dynamic modelling and still need to be verified for decentralized full-scale MBR [52]. Therefore, opportunities to reduce aeration have the potential to significantly reduce overall energy requirements and the SEC in kWh per m^3 of treated water decreases with bigger plant sizes [18]. In the past, the energy consumption by MBR was in the range of 6 and 8 kWh/m^3 (permeate), which was much higher than 0.3–0.4 kWh/m^3 of treated water using ASP. The developments in MBR technology resulted in an energy demand reduction from about 5.0 kWh/m^3, needed for the first side-stream MBRs, to 1.0 kWh/m^3 in 2001–2005 and very recently to about 0.4 kWh/m^3 for the present submerged MBRs [11,53].

4. Conclusion

With the improvement of wastewater treatment process, the increase of membrane manufacturers, and the development of MBR process, as a wastewater treatment and reuse technology in the scattered residential districts, will have more and more outstanding advantages and play an important role in making greater economic and social benefits in practice.

In this research, performances treatment and energetic parameters in the MBR pilot have been monitored. According to the results, the system tends towards a steady state in terms of output parameters provided. This is a fairly constant permeate with a large removal efficiency of TSS and COD, Nitrogen and Phosphorus pollution. The microbiology values in the effluent are quite low. However, the system provide outlet concentrations below a permissible irrigation reuse values given by Moroccan legislation. Regarding the energy consumption based on the results presented in this paper, biological aeration is the major energy consumer, often exceeding 50% share of total energy consumption, followed by the filtration pump. The SEC of an MBR system is dependent on many factors, such as operational parameters, volume of treated flow, and biological reactor performance and membrane utilization. More effort must be given to the aeration supply, in order to minimize the energy demand and thus optimize the cost of the treated water.

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