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# Modelling the link amongst fine-pore diffuser fouling, oxygen transfer efficiency, and aeration energy intensity

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ABSTRACT

This research systematically studied the behavior of aeration diffuser efficiency over time, and its relation to the energy usage per diffuser. Twelve diffusers were selected for a one year fouling study. Comprehensive aeration efficiency projections were carried out in two WRRFs with different influent rates, and the influence of operating conditions on aeration diffusers' performance was demonstrated.

This study showed that the initial energy use, during the first year of operation, of those aeration diffusers located in high rate systems (with solids retention time - SRT-less than 2 days) increased more than 20% in comparison to the conventional systems (2 > SRT). Diffusers operating for three years in conventional systems presented the same fouling characteristics as those deployed in high rate processes for less than 15 months. A new procedure was developed to accurately project energy consumption on aeration diffusers; including the impacts of operation conditions, such SRT and organic loading rate, on specific aeration diffusers materials (i.e. silicone, polyurethane, EPDM, ceramic). Furthermore, it considers the microbial colonization dynamics, which successfully correlated with the increase of energy consumption ($r^2$:0.82 ± 7).

The presented energy model projected the energy costs and the potential savings for the diffusers after three years in operation in different operating conditions. Whereas the most efficient diffusers provided potential costs spanning from 4900 USD/Month for a small plant (20 MGD, or 74,500 $m^3$/d) up to 24,500 USD/Month for a large plant (100 MGD, or 375,000 $m^3$/d), other diffusers presenting less efficiency provided spans from 18,000USD/Month for a small plant to 90,000 USD/Month for large plants. The aim of this methodology is to help utilities gain more insight into process mechanisms and design better energy efficiency strategies at existing facilities to reduce energy consumption.



## 1. Introduction

Supplying oxygen to biomass is recognized as the highest energy use in water resource reclamation facilities (WRRF), accounting for more than 50% of the net power demand (Rieth et al., 1990) and representing a significant fraction of total operating costs

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spanning from 45 to 75% (Rosso et al., 2008; WEF, 2009). Since energy is a major operational component in the present value calculation of treatment costs, improving aeration efficiency and lowering operating costs go hand-in-hand (Reardon, 1995; Rosso and Stenstrom, 2005; WEF, 2009). Continuous research on developing more efficient aeration systems has found fine pore diffusers as a promising avenue to reduce energy due to their higher aeration efficiency (AE, $kgO_2\ kWh^{-1}$), thus they present a competitive advantage in efficiency in comparison to coarse bubble systems (IWA, 2008; Rieth et al., 1990; Rosso et al., 2008b). However, the high maintenance requirements of these systems and their susceptibility to diffuser fouling and ageing reduces their aeration efficiency over time (Gillot et al., 2005; Rosso and Stenstrom, 2006; USEPA, 1989b; Wagner and Popel, 1998). This results in energy required for supplying the same amount of oxygen to the biological process to increase over time which eventually reduces 50% of its original efficiency (Garrido-Baserba et al., 2016a; Rosso and Stenstrom, 2006).

The diffuser deterioration caused by a combination of organic and inorganic foulants and ageing diminishes the OTE (oxygen transfer efficiency, %), increases the backpressure on the blower, and ultimately depresses the system performance and its economic sustainability (Henze, 2008; Kim and Boyle, 1993; Rosso and Stenstrom, 2006). To account for the impacts of fouling on operation with time, a fouling factor, F is introduced:

$$F = \frac{\alpha(t)}{\alpha(0)} \tag{1}$$

where $\alpha(t)$ is the ratio of process to clean water mass transfer coefficients after time t, and $\alpha(0)$ is that ratio at the initial time (i.e., for new or cleaned diffusers). Thus, over time in operation the $\alpha(t)$ factor can be expressed as an agglomerate parameter ($\alpha F$) that equals to:

$$\alpha F = \alpha(t) = \alpha(0) \cdot F \tag{2}$$

While the hydrostatic water head (pressure on the diffuser surface due to the depth of the water column) typically remains constant over the lifespan of the aeration system, the dynamic wet pressure (i.e., the head loss across the diffuser element) increases inexorably with time in operation. Polymeric diffusers experience the additional element of material ageing, quantifiable by variations in rigidity, hardness, and Young modulus (Kaliman et al., 2008; Kim and Boyle, 1993; Rosso et al., 2008a; Wagner and von Hoessle, 2004). Since the DWP rise may place the aeration system operating point near the maximum allowable pressure, that can be safely provided by the blowers, fouling can become the limiting factor of aeration processes and blower operation (Henze, 2008).

Despite the economic drivers, few studies have been conducted to model the fouling phenomena and predict its impact on fine-pore diffusers (Jiang and Rosso, 2010). Restoring the aeration efficiency can create significant operational cost savings (Rosso and Shaw, 2014; Rosso and Stenstrom, 2006). To our knowledge, no study to date has attempted to predict potential aeration costs for fine pore diffusers taking into consideration those variables influencing performance such as operating conditions (e.g., biological process loading rate, solid retention time, diffuser time in operation, etc.), biofilm growth dynamics, and cleaning strategies. In recent years, site-specific considerations have been the basis for aeration performance quantification and prediction, however large uncertainty has persisted. This study presents a comprehensive methodology to predict aeration energy cost with reduced uncertainty.

Some actions on process operations can help treatment plants in curbing the aeration performance decline and energy wastage (Rosso and Stenstrom, 2006). After analyzing the data sets from 103 field measurements, Rosso and Stenstrom (2006) suggested that both process variables (i.e. airflow rate, SRT and influent characteristics) and equipment characteristics (i.e. diffuser type and layout and, intrinsic DWP) impacting the system performance could increase the rate at which diffusers lose their initial performance. These variables can, thus, exacerbate the aeration efficiency decline (Rosso and Stenstrom, 2005).

In an effort to better understand the factors affecting fouling in fine pore aeration systems, we analyzed twelve diffusers over an extended period in operation to obtain a detailed picture of fouling dynamics. The influence of the organic loading rate together with the flowrate and SRT were systematically studied. The influence of the organic load was obtained using two pilot plant studies at two different WRRFs. The same types of diffusers were utilized in both pilot studies, where organic loading rates and influent characteristics were different. The influence of SRT and process loading rate was analyzed using both experimental data from the pilot plants and literature data. The objective was to observe the differences between the main process variables and the influence of the equipment characteristics.

Understanding the influence of each variable on the overall aeration system performance can help WRRFs improve fouling estimations and refine fouling mitigation efforts. While aeration diffuser type has significant impact on short and long-term aeration efficiency (Garrido-Baserba et al., 2016a; Rosso et al., 2005a,b; Rosso and Shaw, 2014), the cleaning strategies, on the other hand, may provide a significant recovery in aeration efficiency and consequently reduce the process energy wastage. Although it is not the objective of this paper to discuss cleaning strategies, or to discuss the characteristics of current available options (i.e., mechanical or chemical cleaning; Rosso and Shaw, 2014; Rosso and Stenstrom, 2005; Sanitaire, 2015; Spellman, 2013; Umur, 2014), the authors acknowledge diffuser cleaning as a required procedure to curb the aeration efficiency decline and consequently to reduce aeration costs. The cleaning frequency and method determine the long-term performance and benefits of using fine-pore diffusers (Rieth et al., 1990; Rosso and Stenstrom, 2006). To effectively utilize the advantages of fine-pore diffuser systems, design and process engineers need information not only on clean and process water performance, but also on fouling propensity and cleaning costs. Therefore, those tools helping to deal with rigorous cost-benefit analysis considering cleaning strategies should be included by practitioners. Understanding the fouling cycle together with more accurate energy projections will maximize the potential economic savings.

The goal of this research was to study the variation of aeration diffuser efficiency over time, while concurrently analyzing the energy consumption variations for each diffuser. We developed a methodology to link diffuser fouling with aeration energy demand, providing a quantitative forecast for aeration energy intensity and cost. Furthermore, we investigated and quantified the impact of process conditions and microbial activity on aeration diffuser performance deterioration.

## 2. Materials and methods

A set of 12 different diffusers were installed in two different WRRFs with low and high loading rates inside two pilot testing tanks. Six diffusers were installed at a water reclamation plant operating in a warm climate area (south California) at low organic rate [SRT:8.0 ± 2.7 d; Mixed liquor suspended solids (MLSS) 2500 ± 400 mg $l^{-1}$] in biological nutrient removal (BNR) mode: 4 membrane tubes (two EPDM, one polyurethane, and one silicone) and two discs (one EPDM and one ceramic). The full-scale process had an activated sludge operating in the modified Ludzack-Ettinger (MLE) configuration (150% internal recirculation) with an average oxygen uptake rate (OUR) of 80–90 mg/L.h. The pilot tank continuously circulated from the first aerated zone of the MLE at average flow of 80 $m^3\ d^{-1}$. The tank was constructed with dimensions of 0.9 × 0.9 × 1.5 m (or 3 × 3 × 5 ft; L × W × D) and was used for both clean and process water tests. The tank continuously circulated activated sludge from the first aerobic zone of the activated sludge process, which is the zone expected to face the worst fouling conditions due to the highest localized oxygen demand. The tank was fed from the bottom and continuously discharged from the top to avoid foam collection. Further details on the field setup are presented in Rosso and Shaw (2014).

Concurrently, an identical set of these six diffusers [4 membrane tubes (EPDM, polyurethane, and silicone) and two discs (EPDM and ceramic)] were installed in another pilot tank installed in a geographical area with four seasons. This full-scale installation was equipped with two activated sludge processes in series (first, a higher rate carbon oxidation only process, followed by a BNR process). The side stream tank was approximately 4,6 m in diameter and 7 m tall (water volume ~50,000l). The tank recirculated on average approximately 4000 $m^3\ d^{-1}$ of activated sludge from the first pass of the higher rate carbon oxidation process [SRT: 2.5 ± 0.4 d; MLSS: 7000 ± 1400 mg $l^{-1}$; OUR: 50–60 mg/L.h]. The side water depth was maintained at 4,7 m, similar as the full-scale process where the sludge was drawn. The tank was fed from the bottom and discharged from the top through a large pipe, to avoid foam collection. This installation was not equipped with DO control.

### 2.1. Aeration performance monitoring

Oxygen transfer in clean water was measured for all diffusers within the air flow range specified by their respective manufacturers using the ASCE standard procedure (ASCE, 2006). Oxygen transfer in process conditions was measured using the off-gas technique according to the ASCE testing protocol (ASCE, 1997). Process-water tests were repeated quarterly to track performance over time and to quantify the fouling factors (F) that represent the ratio of oxygen transfer efficiency deterioration over time.

The diffuser head loss (DWP) was measured to monitor its effects on the aeration energy demand. By measuring the oxygen transfer efficiency and DWP, the blower power demand can be calculated and the degradation of diffuser performance over time can be quantified.

### 2.2. Methodology proposal and rational procedure for energy calculation in aeration

The methodology developed (Fig. 1a and b) is based on one of the first dynamics models to quantify the effect of aeration efficiency and estimate the energy consumption of different treatment processes (Sobhani, 2011). The results obtained are used to calculate the conversion factors for each type of diffuser to determine the impact of process conditions (Table 2). The implementation of these conversion factors in the model enabled the inclusion of the effects of fouling and process conditions in the diffuser energy demand projections. Further details regarding each step of the methodology proposal are available at Supplemental information. The three methodological main steps are:

a) Determination of the oxygen requirements ($R_o$) for biodegradation:

$$R_0 = Q \cdot [S_0 - S] + 4.33 \cdot Q \cdot [NO_x] - 1.42 \cdot P_{X,bio} \quad (3)$$

where Ro is the oxygen required (kg $d^{-1}$), Q is the process flowrate ($m^3\ d^{-1}$), $S_o$ and S are influent and effluent soluble substrate concentrations ($g_{bCOD}\ m^{-3}$), $P_{x,bio}$ is the daily biomass wasting rate ($kg_{VSS}\ d^{-1}$), and NOx is the net nitrogen oxidized ($g_N\ m^{-3}$).

b) Quantification of the oxygen transfer efficiency (OTE) in the activated sludge tanks:

$$OTE = \alpha \cdot SOTE \cdot \frac{[\beta DO_{sat,T} - DO]}{DO_{sat,20}} \cdot \theta^{T_w - 20} \cdot F \quad (4)$$

where θ is the temperature correction factor that ranges from 1.020 to 1.028 for fine-pore diffusers (US EPA, 1989a), and F is the diffuser fouling factor.

c) Calculation of the blower power requirements:

$$BHP_{theoretical} = 1.667 \cdot AFR \cdot P_{inlet} \left( \frac{\gamma}{\gamma - 1} \right) \cdot \left[ \left( \frac{P_{disch}}{P_{inlet}} \right)^{\frac{\gamma}{\gamma-1}} - 1 \right] \quad (5)$$

where BHP is blower brake horse power, $P_{inlet}$ and $P_{disch}$ are blower inlet and discharge pressures, γ is ratio of specific heat at constant pressure and volume (for air = 1.4), and AFR is activated sludge air flow rate. Note that 1.667 is a specific constant for the units used.

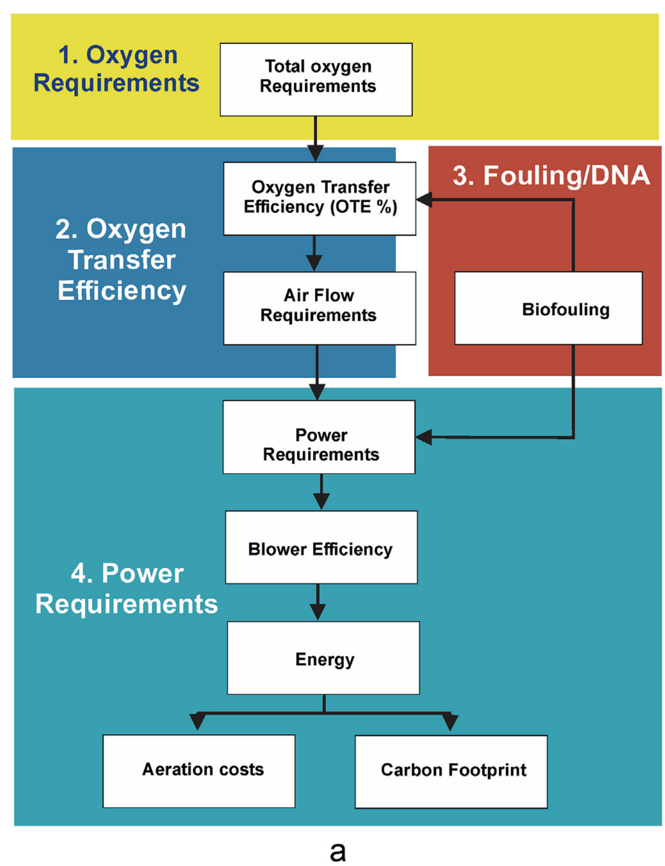
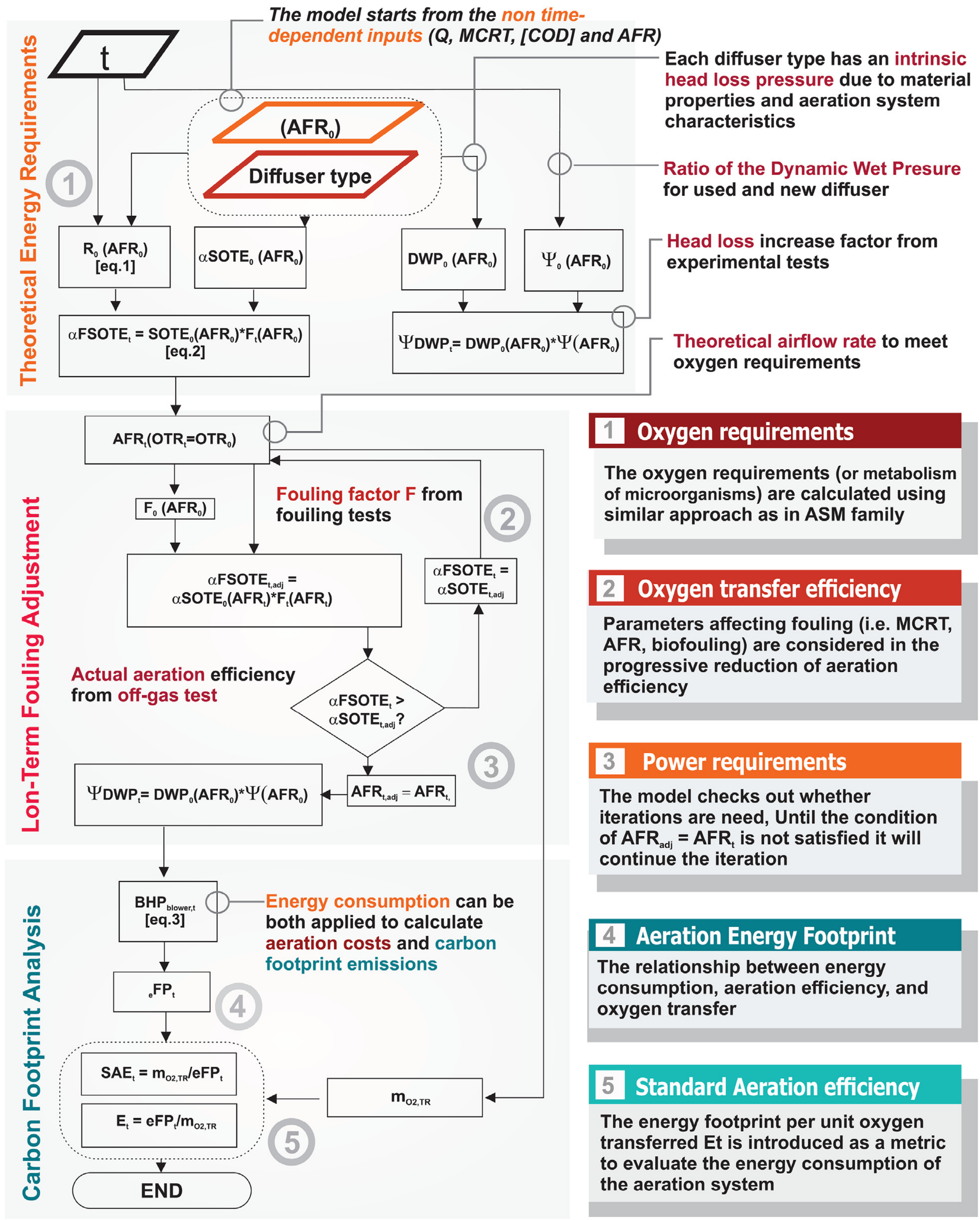



**Fig. 1.** A. Schematic of the rational procedure for aeration cost quantification used for all membrane diffusers. b. Detailed schematic of the rational procedure for aeration cost quantification used for all membrane diffusers.




b

**Fig. 1.** (*continued*).

### 2.3. Molecular biotechnology tools

DNA measurements were proven to be less biased than totals solids to quantify biofilm growth (Asvapathanagul et al., 2012b; Huang et al., 2010). DNA can provide crucial information about the causes and evolution of fouling (i.e. species identification, bacterial consortium composition, life/dead cells, etc.). The following methods have been also extensively applied to the study of the identity and characterization of microbial communities in wastewater treatment plants (Snaidr et al., 1997; Wells et al., 2011; Ye and Zhang, 2012; *inter alia*).

### 2.3.1. Nucleic acid extraction

The extraction method is a modification of Asvapathanagul (2012) which is based on the protocol for mixed liquor samples by (Yu and Mohn, 1999). Three bead beatings (cell lysis) were employed for all samples and then each was resuspended in 30 μL of DNAse/RNAse free water. DNAse Treatment and reverse transcriptase processes were then carried out according to the manufacturer instructions (Lifetechonologies, NY). The same RNA concentrations were used prior to the reverse transcriptase process. Extracted DNA was stored at −80 °C until analysis.

### 2.3.2. Expression of nucleic acid content

The concentration of nucleic acid is expressed as ng of nucleic acid per $cm^2$ of membrane surface.

### 2.3.3. Concentration of DNA

The concentration of DNA was determined on a Nanodrop 10,000 (Thermo Scientific, Wilmington, DE) according to manufacturer instructions. A single reading per triplicate was taken, but periodically throughout the readings the instrument was checked for drift. If the reading was negative, the Nanodrop was zeroed again and the reading redone.

## 3. Results

### 3.1. Loading rate influence

Fig. 2 presents the estimated energy consumption calculated using the aforementioned methodology (Fig. 1b) for the twelve diffusers used in the two pilots operating at different rates (lower rate for the BNR process and higher rate for the carbon oxidation only process) during a period of 15 months. In this figure, the energy consumption is described by power fits, which appear to be the best (in terms of $R^2$) for both comparison purposes and describing both power increase and aeration efficiency decrease (Garrido-Baserba et al., 2016a). In this figure, the data points for αΦ vs. time are not shown to improve plotting clarity (all αF data points are presented in Garrido-Baserba et al., 2016a). For all diffusers tested in this project, the energy consumption steadily increased during the time in operation as a consequence of the erosion in αF, should the same oxygen transfer rate ($mass_{O2}$ $time^{-1}$) be maintained. The pilot tanks were not equipped with DO control, but were operated at fixed air flow, which represents the most conservative boundary since no DO control implies daily periods of anoxia and consequently higher expected fouling rates. Nevertheless, all diffusers installed in the higher rate pilot showed steeper decrease in aeration performance (i.e., OTE, DWP) than diffusers in the lower rate pilot. Most diffusers in the higher rate process (i.e., EPDM Disc, 75 mm EPDM tube, 50 mm EPDM tube, and 50 mm silicone tube) presented higher energy consumption than the lower rate process from the beginning ($t = 0$), which is a combination of the effects of alpha and DWP for the different setups.

The temporal domain of the results can be subdivided in: 1) initial energy consumption (i.e., independent of time); 2) energy consumption increase due to fouling and degradation (i.e., as a function of time). Note that lower alpha values are commonly expected on high loading rate system, as the higher load of contaminants (COD, surfactants, etc.) have the potential to hinder oxygen transfer. It can be seen how 50 mm SI tube, 50 mm EPDM tube and EPDM disc presented different αF values at time 0. Regardless of the initial performance, the actual effect of loading rate conditions is shown by the deterioration rate (i.e., decreasing fit slope) of the air transfer over time. In Fig. 2 the higher rate process presented consistently lower alpha together with a faster decrease over time in comparison to lower rate processes.

The results showed an average energy demand increase of 32% in the 15-month period for those diffusers installed at low rate conditions, whereas an increase of 42% was recorded for those diffusers at high rate (Table 1). Similarly, the decrease in the aeration efficiency parameter alpha factor went from 27 ± 8% at low rate to 37 ± 5% at high rate conditions. These results substantiate the influence of the influent loading rate in the increase of fouling. Thus, in order to project diffuser costs, the effect of the process conditions should be included. Conservatively, it could be stated that for the same treatment requirements an increase in the energy consumption of 10–15% would distinguish the higher from the lower rate processes for the same applied influent. A set of conversion factors were obtained for each type of diffuser (Table 1). Therefore, those plant operators in conventional systems with an SRT close to 8–10 days planning to estimate their aeration costs or modify the influent loading rate may find it useful to apply them to better estimate the impact of the process conditions on their budget.

The rates of increase of energy cost during the 15-months of operation were different among the studied diffusers. Hence, according to the results presented, the fouling after 15 months could cause an additional energy cost in excess of 17,000 USD/month for a typical 20 MGD plant for ceramic disc diffusers. This extra energy cost would exceed 19,000 USD/month in the same plant if EPDM diffusers were installed, according to the results in this test.

These results should be considered conservatively, and care must be used when projecting these results to other locations as some of the site-specific factors affecting the escalation of fouling phenomena are yet to be completely understood. For example, additional power demand and power penalty charges are not considered here. Only a site-specific detailed tariff structure would quantify the actual overall energy costs. In sum, these results are useful for comparison and support of mechanistic analysis of the aeration system dynamics, but design procedures should rely on manufacturer guaranteed data.

### 3.2. SRT influence

The influence of SRT on the aeration efficiency has been studied by different authors (IWA, 2008; Masutani and Stenstrom, 1990; Rosso and Stenstrom, 2005). High SRT is associated with higher MLSS, which results in low loading rates producing higher α factors, in turn improving the overall aeration efficiency while compensating for the additional oxygen demand that occurs at longer SRT. However, other studies indicate a milder inverse relation between MLSS and alpha factor (Krampe and Krauth, 2003; Muller et al., 1995). Similar results were observed in high MLSS-technologies such as MBR-type systems (Fenu et al., 2010). Therefore, the influence of SRT on fouling over time has not been completely clarified. To account for the effect of SRT, off-gas results from 392 tests during a period of 15 years were compiled and analyzed (Rosso et al., 2008b).

Fig. 3 shows how those WRRFs with SRT less than 3.5 days (76 WRRFs) tend to present a significant overall (close to 25%) lower aeration efficiency (2.6 ± 0.78%/m) in comparison to those plants (28 WRRFs) operated atSRT greater than 3.5 days (4.5 ± 1.5%/m). Nevertheless, a clear tendency in either higher or lower SRT plants over time was not statistically yet proven ($P < 0.05$). Considering the available data, the different SRT conditions do not seem to have an observable influence over time ($r^2 < 1$, for both fits). Taking into consideration the results variability among the different plants and

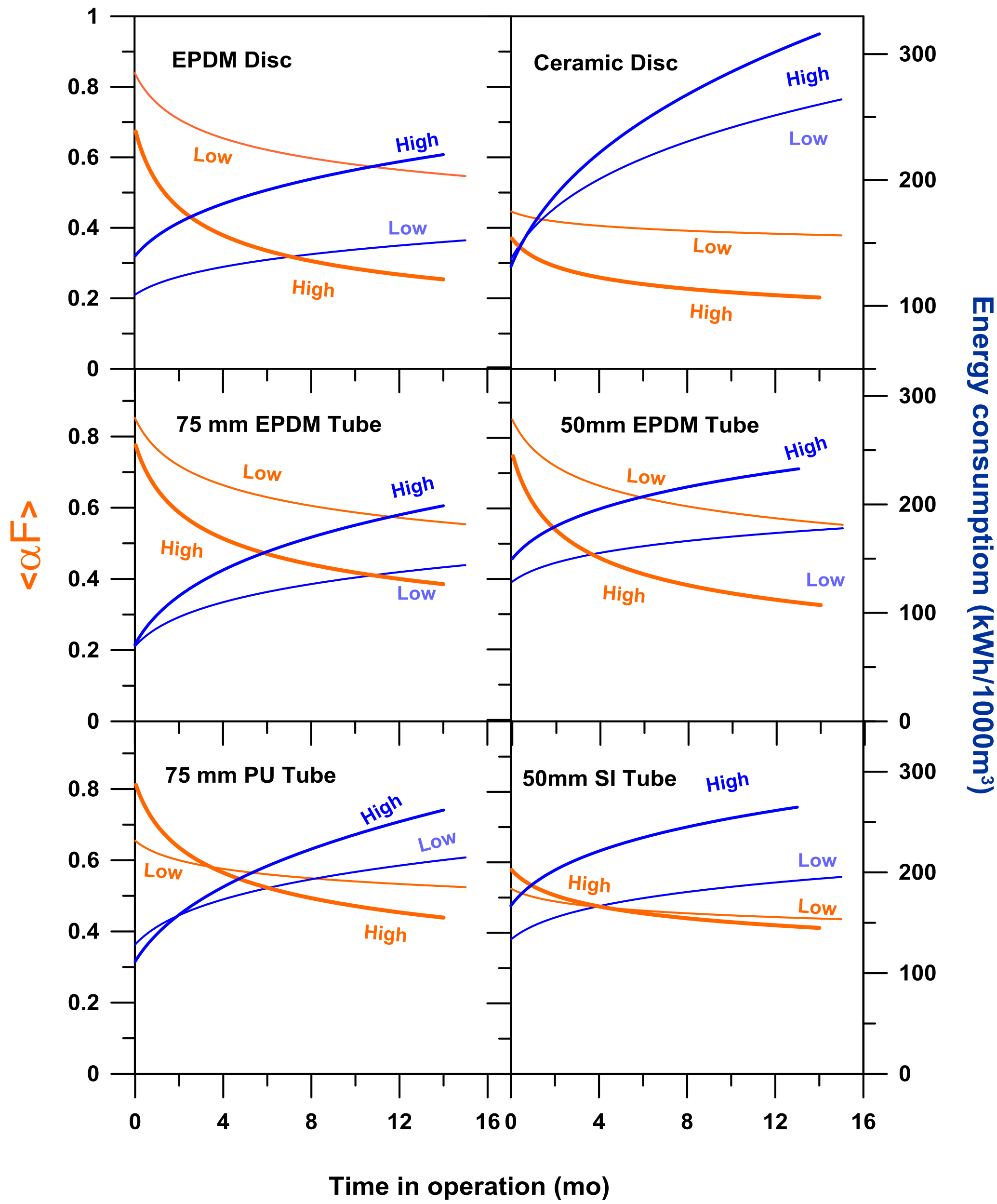



**Fig. 2.** Flow-weighted alpha factor (<αF>) and aeration energy consumption of unit influent versus time in operation for the six diffusers types at high and low rate influent.

**Table 1**
Summary of existing conditions at both WRRFs during the 15 months period.

| Process Parameters | Low Rate (conventional) process | High Rate Process |
|---|---|---|
| Average Flow rate (MGD) | 16 (60,500 $m^3$/day) | 350 (1,300,000 $m^3$/day) |
| Mean Cell Retention Time (d) | 8 ± 2.7 | 2 ± 0.6 |
| BOD, Sec. Influent (mg/l) | 150 ± 28 | 400 ± 70 |
| COD, Sec. Influent (mg/l) | 295 ± 39 | 2500 ± 1500 |
| MLSS, Sec. (mg/l) | 2500 ± 400 | 3500 ± 1000 |
| Ammonia, Sec. Influent (mg/l) | 22 ± 7 | 30 ± 9 |
| Phosphorus (mg/l) | Not measured | 8 ± 4 |

corresponding conditions, the authors would suggest to limit the influence of SRT on the energy projections as an uncertainty factor. Two different power fits to capture the SRT influence were developed in order to create uncertainty and prediction bands, which will be used to provide an improved error margin for the modelled projections. The aeration efficiency of those WRRFs having an SRT greater than 3.5 days or less than 3.5 days will be modelled following an adjustable power fit equations ($\ln(Y) = 0.022_{adj} \times \ln(X) + 1.32$; and $\ln(Y) = -0.065_{adj} \times \ln(X) + 0.97$, respectively).

**Table 2**
Decrease in weighted alpha factor (αF) and increase in aeration energy demand during the 14 months of study for the six diffusers types at high and low rate influent. The corresponding conversion factors to estimate process conditions effect for each diffuser were obtained.

| Diffuser | Energy Increase $E_{t=o}/E_{t=14mo}$ Low rate (%) | Energy Increase $E_{t=o}/E_{t=14mo}$ High rate (%) | αF Decrease $\alpha_{t=o}/\alpha_{t=14mo}$ Low rate (%) | αF Decrease $\alpha_{t=o}/\alpha_{t=14mo}$ High rate (%) | Energy Factor $E_{LR}/E_{HR}$ | Increase Fouling $\alpha_{t=o}/\alpha_{t=14mo}$ |
|---|---|---|---|---|---|---|
| 250 mm EPDM DISC | 24.9 | 41.6 | 34.1 | 44.7 | 0.6 | 1.8 |
| 250 mm Ceramic disc | 41.8 | 53.8 | 25.6 | 37.4 | 0.5 | 1.6 |
| 75 mm EPDM tube | 25.7 | 22.9 | 34.4 | 41.6 | 0.8 | 1.7 |
| 50 mm EPDM tube | 27.1 | 36.3 | 34.4 | 38.8 | 0.6 | 1.6 |
| 75 mm PU tube | 41.8 | 66.2 | 19.5 | 33.3 | 0.3 | 1.5 |
| 50 mm SI tube | 31.2 | 27.2 | 16.1 | 28.7 | 0.7 | 1.4 |
| **Average ± STD** | **32 ± 7** | **41 ± 14** | **27 ± 8** | **37 ± 5** | **0.6 ± 0.2** | **1.6 ± 0.14** |

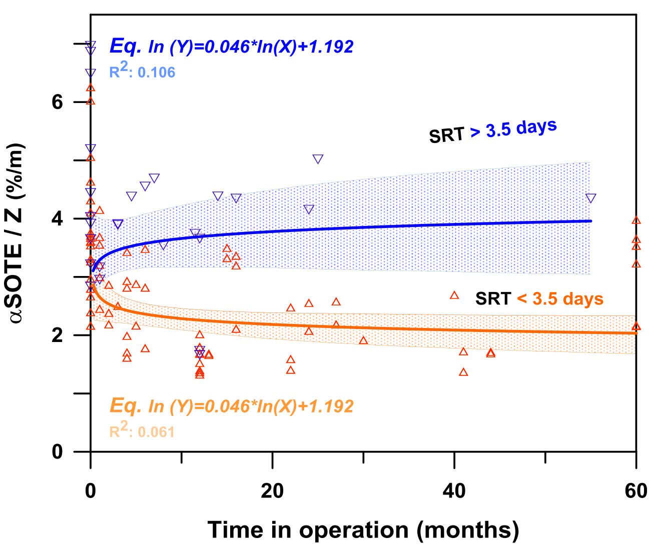



**Fig. 3.** Alpha Standard Oxygen Transfer Efficiency per depth (αSOTE/Z) of 103 WRRFs in operation from 0 to 60 months. The WRRFs have been divided into those having a Mean Cell Retention Time (SRT) less than 3.5 days and those having a higher SRT than 3.5 days. The plots are power fits of datasets from 103 off-gas test and their corresponding interval of confidence (95%).

### 3.3. Biofouling influence on the decrease of αF

Recent studies have demonstrated that the performance of aeration diffusers in process water was consistently eroded by biofilm growth on the diffuser surface, which indicated a direct correlation between the decreased aeration efficiency parameters with biofilm growth (Asvapathanagul et al., 2012a; Garrido-Baserba et al., 2016a, 2015; Rosso and Shaw, 2014). The decrease in efficiency parameters, such as the fouling factor, over time is not exclusively due to biofouling. Other phenomena like inorganic scaling or diffuser material ageing also contribute to the overall decrease of aeration performance. However, the influence of the microbial activity on these phenomena enhance them proportionally (Garrido-Baserba et al., 2016b), indicating that the use of biofilm growth (expressed as DNA concentration) can be a robust fouling indicator (Garrido-Baserba et al., 2016a). Therefore, in this study we analyzed the DNA concentration in the diffuser fouling biofilm to improve the estimation of the αF decrease and consequently gain insight into the future costs projections.

Fig. 5 shows the effects of two loading rates (higher and lower) on the fouling factor <F> and the concurrent increase in DNA concentration for two diffuser material types (EPDM and polyurethane). By definition, new diffusers have fouling factor, $F = \langle F \geq 1.0$, and it can be seen how the fouling ratio decreased over time. The oxygen transfer efficiency is eroded (quantified by the fouling factor) as time in operation progresses, as a result of the concurrent microbial biofilm growth (quantified by the DNA on the diffuser surface). Also, in Fig. 4 we can see the differential effect of process loading on EPDM membranes, whereas the polyurethane material seems less affected.

In order to see if the correlation between <αF> and biofilm growth was also dependent on process conditions, a comparison between the low and high rate processes (Fig. 4) was carried out by comparing both biofilm mass and aeration performance parameters for all of the diffusers that were installed in both pilots. Fig. 4 shows the results of DNA quantification in both WRRFs during the 15 month period, and the concurrent time-series of flow-weighted <αF>. For all diffusers tested in this project, the biofilm growth ensued while the efficiency parameters steadily decreased during the time in operation. A decreasing trend in <αF> appears to find a stabilization value around 0.4 for the higher rate influent process and around 0.5 for the lower rate process after 24 months in operation. In all plots, the DNA increase is also described by power fits, which properly are non-limited functions, however they appear to best describe the phases from transient growth to steady state observed experimentally. During the 15 months period, a plateau was not strictly observed, yet the decreased pattern of fouling values appear to bottom at a plateau value, suggesting a maturation of the biofilm or at least of its effects.

To better represent and understand long-term dynamics of αF

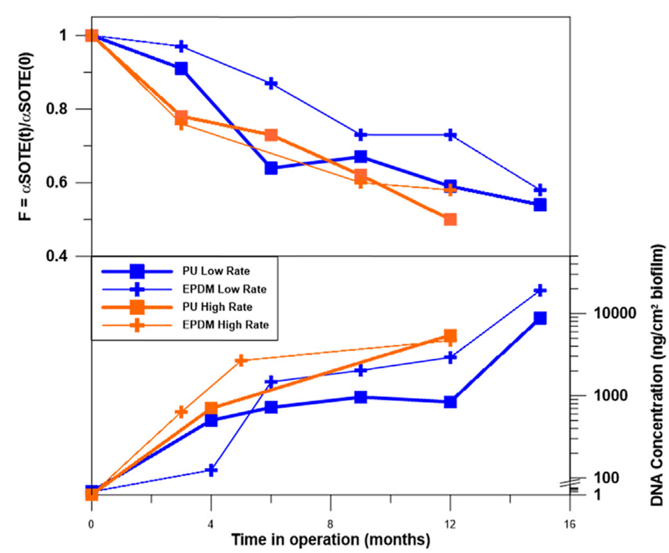



**Fig. 4.** Effects of different influent rates on aeration performance for two diffuser membrane materials (Square symbol - PU = polyurethane; Cross Symbol - EPDM) at midrange air flux. Note that the DNA concentration, a quantification of the biofilm mass, is in log-scale.

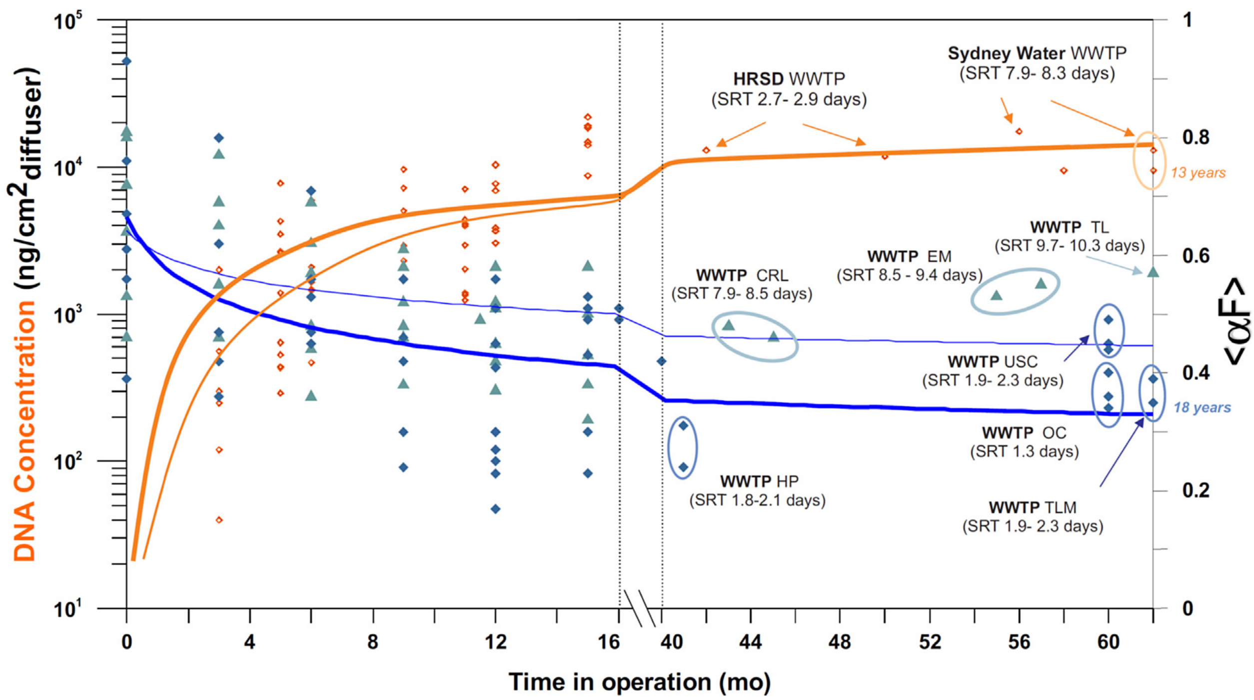



**Fig. 5.** Diffuser biofilm increase (expressed as DNA concentration) over the project period (15mo) for the five fine-pore diffusers at higher rate conditions (thicker orange) and lower rate conditions (lighter orange), together with the flow-weighted fouling values at higher rate conditions (thicker blue) and lower rate conditions (lighter blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and DNA increase the aforementioned off-gas results from 103 tests in Fig. 3 (Rosso et al., 2008b) were coupled with the 15 months of project measurements (Fig. 5). Fig. 5 shows how the decrease in aeration efficiency (αF) is not fully correlated by the DNA concentration increase. An ideal correlation between αF and DNA increase would show how both high and low <αF> values would meet after 12 months. However, taking into account literature and project data it can be seen how operational conditions may result in an approximate 20% decrease between higher rate (HR) and lower rate (LR) processes, a difference which is not being paralleled by the total DNA concentrations dynamics.

Fig. 6 plots the energy consumption (kWh/1000 $m^3$) for the lower rate fine-pore diffusers during the project period (15 months) as a function of the corresponding DNA increase. Fig. 6 shows the increase in energy consumption is directly correlated to the increase of the biofilm growth. All membranes exhibited an energy increase, with the 50 mm EPDM and 50 mm silicone tubes being the least energy intensive whereas the ceramic disc was the most energy intensive.

The direct correlation between DNA concentration and energy consumption is evident. The average coefficient of determination between biofilm DNA concentration and energy demand for the six diffusers was $R^2 = 0.74 \pm 0.07$ (Fig. 6). The coefficient of determination for 50 EPDM, SI and EPDM disc were 0.84, 0.81, and 0.77 respectively, whereas PU exhibits the lowest ($R^2 = 0.64$). Although each diffuser type presents its own energy consumption and specific fouling response, the overall results provide the evidence on the mechanistic relation between energy demand and fouling phenomena (a combination of biofouling, scaling, and material ageing) expressed as DNA concentration.

This correlation can be used to improve the previous energy predictions. The dynamics of the biofilm growth, which tends to reach a plateau, can be used to correct and tune the cost projections. Thus, energy projections based on each of the observed biofilm growth trends over time were incorporated using the corresponding model equations for each type of membrane and process conditions in order to simulate their future cost analysis. Conservatively, the projections were applied to those membranes installed in the lower rate process to provide realistic cost prediction on the decreased fouling and, particularly, to determine the cost escalation over time, together with the potential cost savings that cleaning strategies could have on each specific diffuser type. Although the exact efficacy of cleaning methods is not yet well documented and established, some studies have shown the capacity to restore efficiency by more than 75% in relative terms (Kaliman et al., 2008; Rosso and Shaw, 2014; Umur, 2014). In order to show the relevance to forecast the energy demand of aeration diffusers, this study calculated the potential benefits when cleaning strategies were applied after a 15 months period, leading to a theoretical recovery of 75% of the initial diffuser performance used to operate them during three years (Fig. 7).

### 3.4. Energy projections

Figs. 8 and 9 present conservative energy projections for the diffusers' operation. The initial 15 months correspond to real data, whereas from 15 to 32 months we present extrapolated values. The uncertainty band was calculated using the observed variations in both 1) process variables (i.e., influent characteristics, expected changes in process conditions, effluent target); and 2) equipment variables (i.e., diffuser type and number, DWP, oxygen transfer efficiency). Conservatively, three intervals of confidence based on these variable were applied: 10% (t = 15–21mo); 12.5% (t = 21–26); 15% (t = 27–32).

Figs. 8 and 9 are the results of diffusers' aeration performance (aeration costs increase along the time in operation) and it can be seen the potential savings of the diffuser-types.

Fig. 8 shows that the EPDM disc has a lower initial energy intensity than the ceramic disc (103 kWh/1000 $m^3$ and 134 kWh/1000 $m^3$, respectively), but the EPDM disc experiences a higher

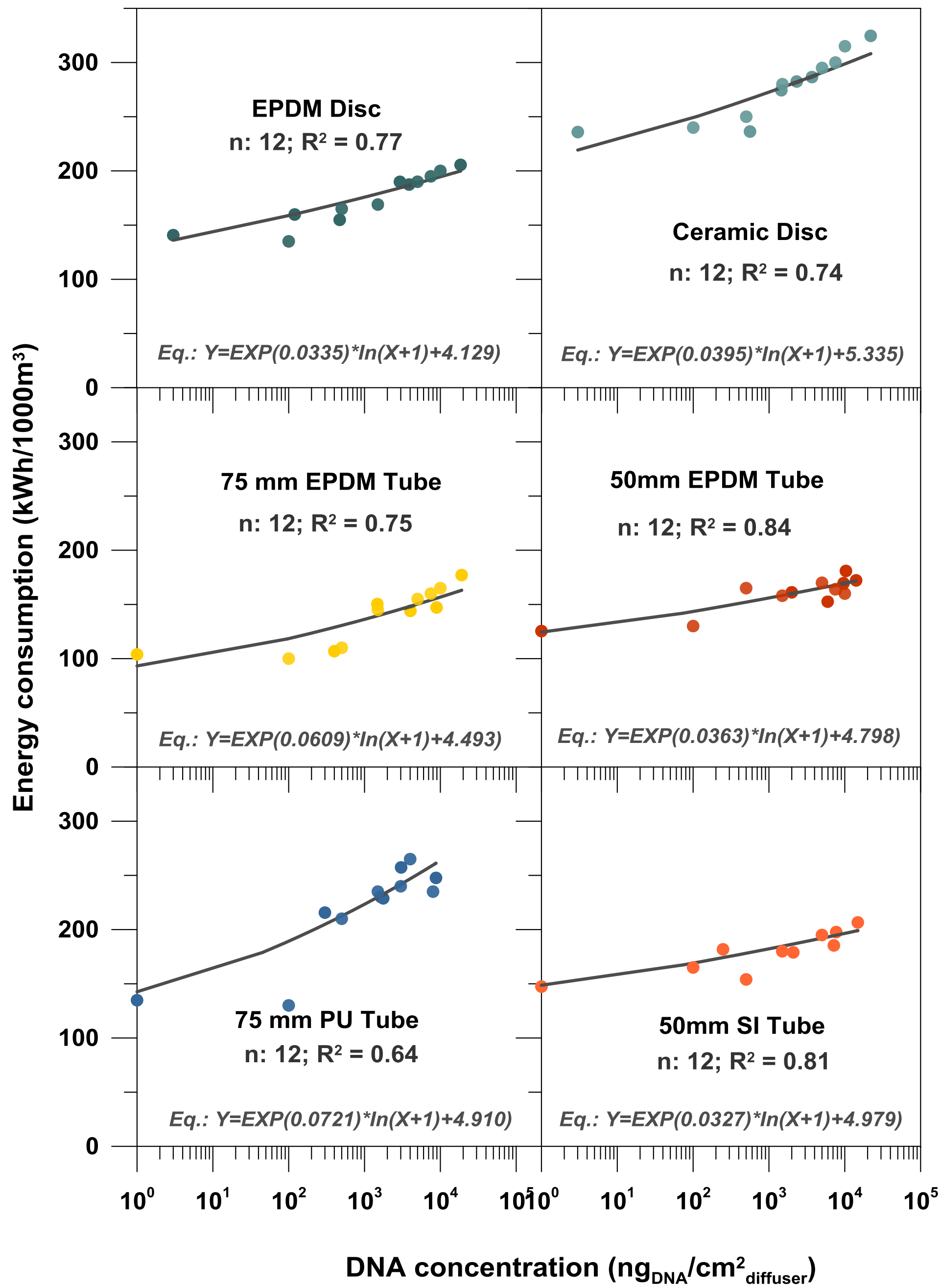



**Fig. 6.** Correlation between energy consumption calculates with the aforementioned methodology and total biofilm DNA concentration for the six membranes. For each plot the coefficient of variation never exceed the value reported.

energy consumption increase at t = 15 mo (27% vs. 22%, respectively). Once the projection cost model is applied, a lower increase is observed from the later period from t = 14mo to t = 32mo (6.5% and 5.9%, respectively), indicating that the initially rapid decrease in performance is mainly due to the increase in biofilm growth. Similarly, the rest of the diffusers tested also show a more moderate increase from 15 m to 32mo in comparison to the initial period 0–15 months.

Note that the average increase after 36 months resembles that experienced at 15 months for those diffusers installed in the higher rate process (0.41 ± 0.05), indicating that high rate processes may contribute to shortening the diffuser life expectancy by two to three fold due to the effect of the microbial activity (biological aging). The estimated cost savings for a 2 year forecast considering the same rate of fouling for a plant of 74,500 $m^3$ $d^{-1}$ (or 20 MGD) would represent savings for EPDM and ceramic discs of approximately 110,000 and 90,000 USD (assuming an energy price of $0.1/kWh), respectively (Fig. 8), whereas for 50 and 75 mm EPDM tubes, SI tube, and PU tube, the savings would be closer, 115,000, 190,000, 200,000, and 53,000 USD, respectively (Fig. 9).

## 4. Discussion

The quantitative correlation between biofilm growth and energy consumption was identified. Biofilm DNA measurements over time were observed to be a reliable indicator of the decrease of

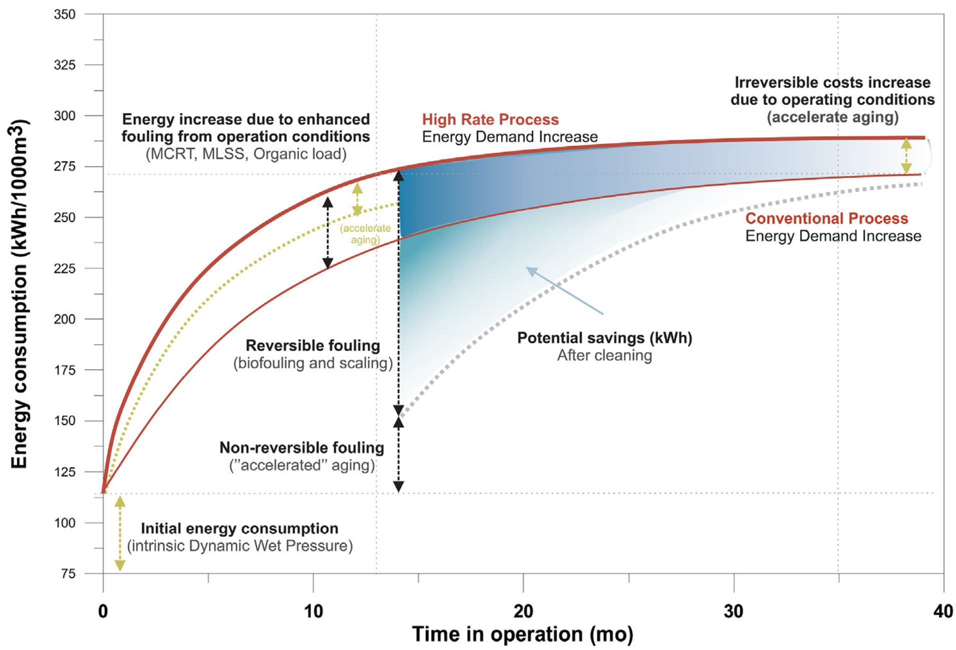



**Fig. 7.** Hypothetical representation of the operating conditions (high rate process vs conventional system) impact on the aeration diffusers fouling and concurrently on the energy demand (Summary figure designed after analyzing the project results).

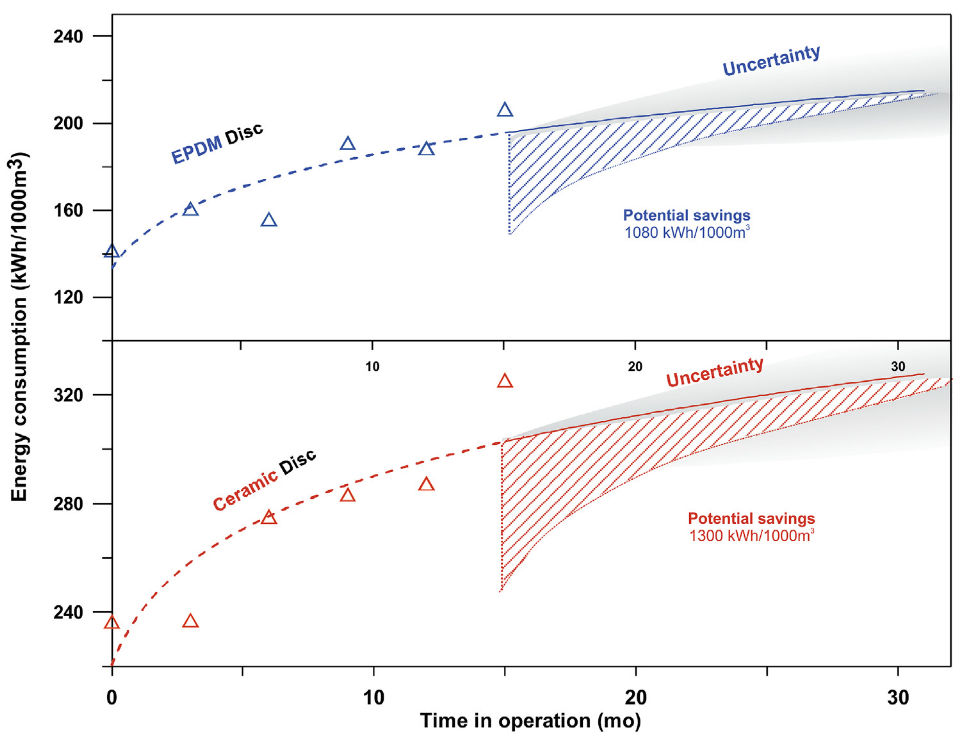



**Fig. 8.** Energy consumption of the EPDM and ceramic disc diffuser over the 15 months period and the corresponding energy projections and estimated potential savings during the period from 15 to 32 months.

efficiency parameters concurrently with the energy consumption. Fig. 6 showed that while the trend in DNA concentration for both high and low rate processes was to merge towards the same concentration over time, it could be seen how αF seems to slightly depart, with the higher rate processes αF more eroded. For the high rate influent process αF seems to find a stabilization value at 0.40, whereas the lower rate plateau is around 0.48. The observed αF differences between the two different processes could be attributed to a more pronounced diffuser fouling in the higher rate process associated with more enhanced microbial activity on the diffuser surface, accelerating material properties deterioration (biologically-enhanced material aging). Although DNA concentration was demonstrated to properly describe the dynamics of αF (Garrido-Baserba et al., 2016a; 2016b), being a reliable indicator embracing

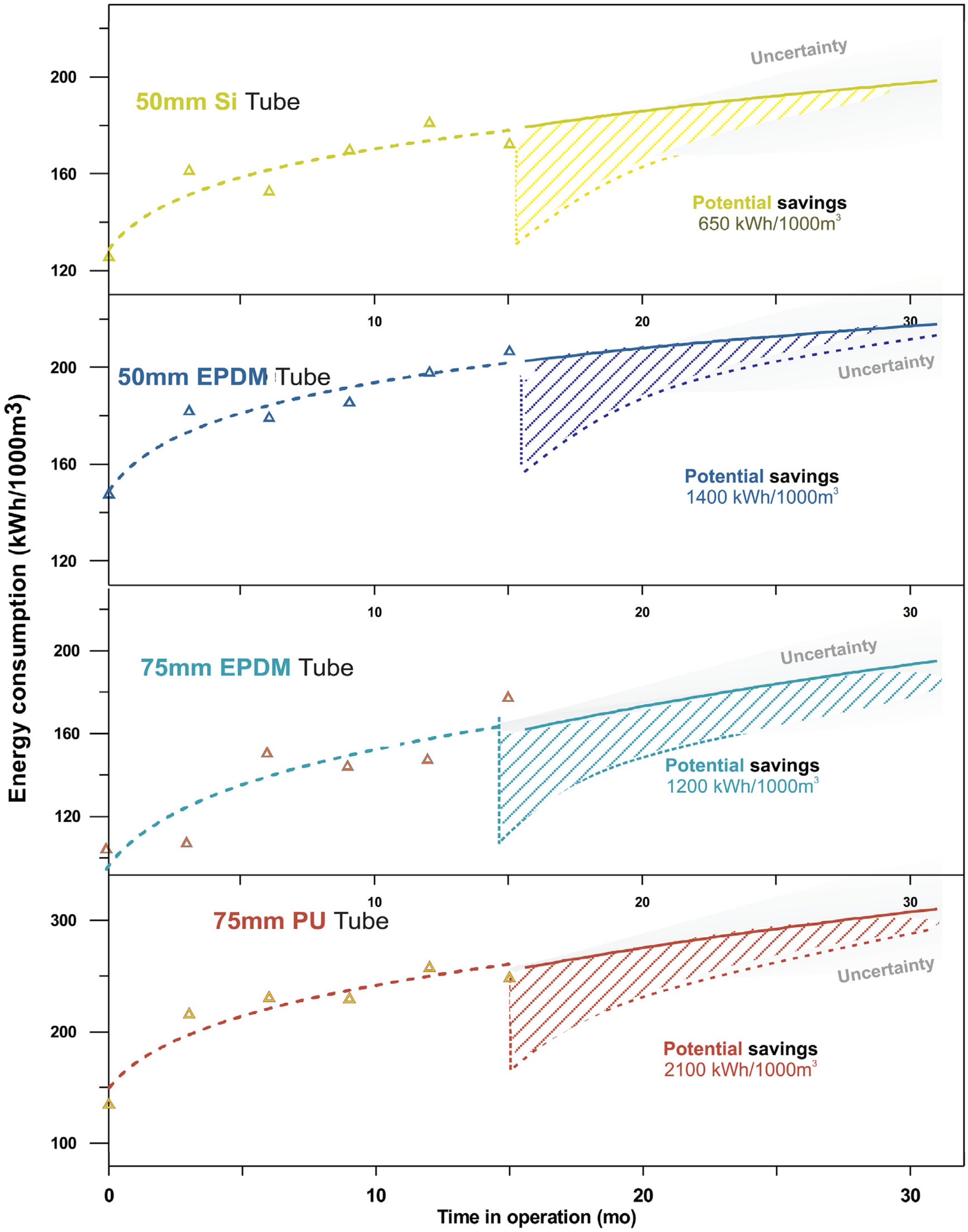



**Fig. 9.** Energy consumption of the 75 mm and 50 mm tube diffuser during the 15 month period and the corresponding energy projections and estimated potential savings during the period from 15 to 32 months.

the different phenomena influenced by microbial activity (biofouling, scGarrido-Baserba et al., 2016aaling, and biological aging), it can be seen how the energy consumption for both processes do not follow the same merging dynamics as DNA concentration, which suggested that both higher and lower rate αF would meet after 12–16 months. However, despite the convergence of the two average DNA curves after 12–16 months, the αF curves exhibit a permanently set difference in plateau.

Note that the mechanistic relationship between air flux and biofilm growth was not established in this study. However, since the air flux is proportional to the oxygen demand, a correlation between diffuser air flux and biofilm growth can be observed, given that higher oxygen demand is equivalent to higher substrate availability for the biofilm growth. Future studies should investigate the biofilm population dynamics in relation to the substrate nature and to the storage products that are associated with biofilm growth and consequently with an increase in energy intensity for aeration.

Regarding the energy projections, it has to be noted that those diffusers presenting higher costs after a 3 year period may not be the ones presenting the higher overall potential savings once an appropriate cleaning strategy is applied. Some diffusers like 50 mm SI had higher initial consumption (129 kWh 1000 $m^{-3}$) than 75 mm EPDM (95 kWh 1000 $m^{-3}$), however its stable performance and slight increase point out this type of diffuser may be a good option to reduce operational costs and avoid cleaning strategies. On the other hand, 75 mm PU presenting a sharper slope may require higher-frequency cleaning to enhance performance and increase cost savings. We projected that the potential energy savings achieved with fouling prevention could span from 18,000 USD $mo^{-1}$ for a small plant (20 MGD, or 74,500 $m^3$ $d^{-1}$) to 90,000 USD $mo^{-1}$ for a large plant (100 MGD, or 375,000 $m^3$ $d^{-1}$).

The results (Figs. 8 and 9) show that when utility managers and engineers need to select the diffuser type, they need to consider not only the initial energy demand of the selected diffusers, but also the energy consumption escalation of each diffuser over time (due to diffuser fouling and degradation). While the design procedure is underway, in situ candidate diffuser tests provide parallel site-specific testing opportunities to obtain αFSOTE and ΨDWP (e.g., details in Rosso et al., 2012). This practice minimizes the uncertainty associated with the aeration design procedure. Life-cycle cost analysis should always be embraced as the proper decision-making procedure in aeration systems selection and operation.

## 5. Summary and conclusions

The influence of operating conditions on aeration diffusers' performance was demonstrated. Our study showed that aeration diffusers installed in higher rate processes experience an additional erosion of their initial performance that exceeds 10% (in relative terms) during the first year, when compared to the same diffusers installed in lower rate processes. Diffusers in operation for 36 months in lower rate processes presented the same fouling characteristics as those that were deployed in higher rate processes for less than 15 months.

A new procedure to accurately project energy demand on aeration diffusers was developed. The main characteristics included in the approach are the inclusion of the effect of operating conditions (e.g., SRT and $BOD_5$) on specific geometry and material of aeration diffusers (i.e., discs and tubes; silicone, polyurethane, EPDM, ceramic) together with the consideration of the microbial colonization dynamics, which were successfully correlated with the increase in aeration energy demand ($r^2 = 0.82 \pm 7$).

Our energy model enabled the projection of the expected costs for the diffusers after three years in operation. To illustrate the direct benefits of knowing the actual operational costs for each type of diffuser, an estimation was carried out and a fouling reduction of 75% in case of assumed typical cleaning was applied. Whereas some diffusers provided potential savings spanning from 4900 USD $mo^{-1}$ for a small plant (20 MGD, or 74,500 $m^3$ $d^{-1}$) to 24,500 USD $mo^{-1}$ for a large plant (100 MGD, or 375,000 $m^3$ $d^{-1}$), other diffusers presenting lower efficiency span from 18,000 USD $mo^{-1}$ for a small plant to 90,000 USD $mo^{-1}$for a large plant.

The main contributors to the increase in energy costs were identified. The methodology to quantify and predict the performance of specific types of diffusers was developed including the previously identified sources of uncertainty. The standardization of the results from same type-diffusers at different process conditions could lead to better predictions and improve the quality of the energy demand projections. The presented life-cycle cost –based methodology aims at serving as a quantitative tool to support aeration system selection, design, and maintenance by utility engineers.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2016.12.027.

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