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Industrial effluent treatment with immersed MBRs: treatability and cost

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Abstract

A comprehensive OPEX analysis for both municipal and industrial wastewaters has been conducted encompassing energy, critical component (membrane) replacement, chemicals consumption, waste disposal and labour. The analysis was preceded by a review of recent data on industrial effluent treatability with reference to published COD removal data for four effluent types: food & beverage, textile, petroleum and landfill leachate.

Outcomes revealed labour costs to be the most significant of those considered, contributing 50% of the OPEX for a 10,000 m^3/day capacity municipal wastewater treatment works. An analysis of the OPEX sensitivity to 12 individual parameters (labour cost, flux, electrical energy cost, membrane life, feed COD, membrane cost, membrane air scour rate, chemicals cost, waste disposal cost, mixed liquor suspended solids (MLSS) concentration, recirculation ratio, and transmembrane pressure) revealed OPEX to be most sensitive to labour effort and/or costs for all scenarios considered other than a large (100,000 m^3/day capacity) works, for which flux and electrical energy costs were found to be slightly more influential. It was concluded that for small-to-medium sized plants cost savings are best made through improving the robustness of plants to limit manual intervention necessitated by unforeseen events, such as electrical/mechanical failure, foaming or sludging.

Keywords: Membrane bioreactor; treatability; operating cost; industrial effluent; sensitivity

Introduction

Membrane bioreactors (MBRs) offer an alternative to treatment by the conventional activated sludge (CAS) process when a relatively high-quality effluent is required, specifically with reference to the colloidal, phosphorus and/or microbial content (Judd, 2011). In such cases the CAS process must be fitted with tertiary treatment (or “polishing”) to attain a comparable water quality. Most comparative cost analyses from the past decade have concluded that, for moderate to large scale installations, the capital cost (CAPEX) of large-scale MBRs tend to be slightly lower than the CAS + polishing alternative (Brepols et al, 2010; Young et al, 2013; Iglesias et al, 2017) particularly when (a) available space is at a premium and/or costly, or (b) polishing employs membrane filtration (Iglesias et al, 2017). However, it is also the case that operating expenditure (OPEX) is generally higher due to the requirement for scouring of the immersed membrane by coarse bubble aeration.

Thus far quantification of the operational parameters impacting on OPEX have tended to focus on energy consumption generally (Díaz et al, 2017; Krzeminski et al, 2017; Tang et al, 2018), and the membrane air-scour energy of an iMBR in particular (González et al, 2018; Miyoshi et al, 2018; Wang et al, 2018). Recent reports suggest specific aeration demand (SAD) values of 0.13-0.3 $Nm^3.h^{-1}$ per m^2 membrane area (Wang et al, 2018; Miyoshi et al, 2018), or as low as 6-8 Nm^3 per m^3 permeate (Díaz et al, 2017) depending on the membrane configuration. This has led to reported mean energy consumptions in the region of 0.35–0.65 kWh per m^3 permeate for large municipal iMBR installations commissioned after 2014 in China (Xiao et al, 2019).

There have thus been significant economies made over the past ten years in energy consumption. Coupled with this has been steadily decreasing membrane replacement costs, due to decreasing purchase prices coupled with demonstrated extended membrane life (Côté et al, 2012). It is thus prudent to consider the sensitivity of OPEX to all contributing factors, namely energy and chemicals consumption, membrane replacement, plant servicing (i.e. labour), and waste disposal. Since OPEX is highly dependent on the feedwater quality, and specifically the energy demanded by the aerobic degradation of the feedwater organic and amino/ammoniacal substances, the feedwater characteristics must also be taken into consideration.

In the current paper the sensitivity of the overall OPEX to 12 individual operating parameters is computed for four scenarios based on municipal and industrial wastewater treatment by an iMBR. Governing empirical equations for individual OPEX contributions are taken from or informed by literature information/data. The OPEX analysis is preceded by an appraisal of industrial effluent treatability, based on published COD removal data for four generic effluent types, since this impacts significantly on the microbiological (or "process") energy demand.

Methods

Data sources

Wastewater quality and treatability

A single medium-strength municipal wastewater quality was used as a benchmark, informed by various reference texts such as Tchobanoglous et al, 2003. Industrial wastewater quality and treatability data was obtained from the reference of text of Judd (2014) for full-scale case MBR studies, along with the review articles by Lin et al (2012), Larrea et al (2014), Hashisho and El-Fadel (2016) for landfill leachate and Jegatheesan et al (2016) for textile wastewaters. These data were embellished by more recent data extracted from peer-reviewed literature and conference publications published predominantly from 2010 onwards. COD removal data trends were formed from at least 10 data points for the four different industrial effluent types (see supplementary data).

Operation and maintenance (O&M)

O&M data, and specifically those relating to flux, membrane aeration and chemical cleaning frequency, were taken from Judd (2011, 2014). These data were supplemented with available data from the operation of full-scale industrial effluent treatment installations.

Costs

Energy consumption is based primarily on air and liquid pumping, with air pumping demanded for the process biology tank and, in the case of immersed membranes, membrane scouring. Liquid pumping relates to permeate extraction and sludge transfer between tanks. To maintain consistency the analysis was restricted to the Modified Ludzack-Ettinger (MLE) configuration for two-stage nitrification-dentrification. The specific aeration demand for the biochemical process (SAD_{bio}) was determined based on standard bio-stoichiometric relationships, as outlined in reference texts such as Tchobanoglous et al, 2003 and Judd (2011). The small amount of electrical energy for monitoring and control was ignored in this analysis

A mean membrane cost was assumed based on information from suppliers and end users. Chemicals were assumed to be used solely for membrane cleaning. Published analyses, partly based on data from full-scale operating plant, suggest this cost contributes 7-15% to the total OPEX (Brepols et al, 2010; Young et al, 2013). In the current study, the permeate-normalised chemicals consumption cost, L_C, was based on fixed-interval maintenance cleaning using sequential hypochlorite and citric acid cleans of fixed duration. Sodium hypochlorite and citric acid costs of $\$800.t^{-1}$ and $\$500.t^{-1}$ were assumed for 15% and 50% stock solutions respectively. These were assumed to be dosed at 0.04 and 0.2% respectively for 30 minutes each at twice the forward flux (J) during a twice-weekly maintenance clean.

Sludge disposal costs are very location specific. A past comparison of landfill disposal costs revealed this to be less than \$100 $teDS^{-1}$ (dry solids) in the US compared with more than \$250 $teDS^{-1}$ in Europe, and a more recent analysis as being €20-100 per te sludge (Bertanza et al, 2015). The contribution of waste disposal to overall OPEX has been calculated as being 8-16% (Brepols et al, 2010; Verrecht et al, 2010). In the current analysis a mean disposal cost (L'_{DS}) of \$100 $teDS^{-1}$ has been assumed. Since the DS generated is directly related to the COD by the observed sludge yield (Y_{obs}), waste disposal costs are roughly proportional to the feedwater COD provided Y_{obs} is constant.

Information on staffing levels was taken from three sources: (a) Ovivo MBR plant installations (Ovivo, 2018), providing 6 data; (b) the Missoula wastewater treatment staffing assessment (Cormier and Murphy, 2013), 8 data, and (c) the Northeast guide for estimating staffing at publicly and privately owned wastewater treatment plants (Poltak, 2008). The Poltak (2008) report advocates a method in which full-time equivalent (FTE) hours are assigned to specific pieces of equipment, infrastructure or tasks. For comparability with the two other data sets, only the operator effort was considered from this analysis, encompassing ancillary costs. The labour cost at a given plant capacity is then given by the FTE multiplied by the gross salary (paid salary + employer's tax + overhead). The complete data sets of (a)-(c) were used to generate the algorithm for normalised FTE (FTE per unit flow Q) vs. Q.

Labour cost was assumed to be the only cost component to change with flow, although it is recognised that at very low flows sub-optimal operation prevails due to equipment oversizing. Such impacts on OPEX were assumed to be insignificant at the lowest flow of 2,000 $m^3.d^{-1}$ considered in the current study.

Base parameter values and algorithms

Selected base parameter values sourced from literature are given in Table 1. The governing equations for determining main specific energy consumption (SEC, denoted E) and other cost contributors (Table 2) dictate SAD_{bio} to be a function of (i) the concentration of COD and Total Kjeldahl Nitrogen (TKN) removed (yielding the oxygen demand D_{O2}), and (ii) the physical relationships linking the energy required to pump the air (E'_A) with the efficiency of oxygen transfer into the sludge. The latter relates to the alpha factor (α), for which many authors have presented empirical correlations with sludge concentration.

Scenarios

The analysis considers four scenarios (Table 3) encompassing different flows and feedwater COD and TKN loads according to the plant size and feedwater type (municipal or industrial). Results are presented as (a) contributions from the five main cost factors (L in \$ per m^{-3} permeate) of total energy ($L_{E,tot}$), membrane replacement (L_{MR}), chemical consumption (L_C), Labour (L_L), and waste (L_W), and (b) % cost sensitivity. The sensitivity of overall OPEX (L_O) to a 20% change in a specific parameter was computed for 12 parameters: feed COD and MLSS (X) concentration, net flux (J), transmembrane pressure (TMP), specific aeration demand for membrane scouring (SAD_m), recirculation ratio (R), electrical energy cost (L_E), membrane cost (L_M), membrane life (t), chemicals cost (L_C), labour cost (L_L) and waste disposal cost (L_W). A

20% increase was computed for all parameters other than cost and membrane life, for which a 20% decrease (i.e. a 20% improvement) was computed for comparability

Table 1. iMBR operational process parameter base values

Parameter	Symbol	Value(s): Base, range
Aerator depth, process, membrane tanks, m	h	5, 3.5
Air density, g.m^{-3}	ρ_A	1.23
Alpha factor	α	*Section 4.1*
Biomass COD, TKN content, kg.kgSS^{-1}	λ_{COD}, λ_{TKN}	1.1, 0.095
Change in COD, TKN, NO_3^- concs., g.m^{-3}	ΔS_{COD}, ΔS_{TKN} , $\Delta S_{Nitrate}$	*Section 4.2*
Chemicals consumption costs, \$.m^{-3} permeate	L_C	0.031[a]
Conversion (permeate/feed flow)	Θ_{MBR}	96%
Electricity supply cost, \$.kWh^{-1}	L_E	0.1
Labour costs, \$.m^{-3} permeate	L_L	*Section 4.3*
Mass consumption of oxygen, g.m^{-3}	D_{O2}	Calculated (Table 2)
Mass transfer correction factors for oxygenation, -	β, γ	0.95, 0.89
Membrane cost, \$.m^{-2} membrane area	L_M	30
<u>Membrane life, hrs</u>	<u>t</u>	<u>52560, 70080</u>
Membrane-biological process tank recycle ratio, -	R	4
MLSS concentration, process tanks kg.m^{-3}	X	8
Observed sludge yield, kgSS.kgCOD^{-1}	Y_{obs}	0.35
Oxygen content of air, %	C'_A	21%
Oxygen transfer efficiency per unit depth, m^{-1}	OTE	0.045
<u>Permeate flow rate (plant capacity), m^3.d^{-1}</u>	<u>Q_P</u>	<u>2,000, 10,000, 100,000</u>
Permeate net flux, industrial, municipal, L.m^{-2}.h^{-1}	J	15, 20
SAD, biological aeration, Nm^3.m^{-3} permeate	SAD_{bio}	Calculated (Table 2)
SAD, membrane scouring, Nm^3.m^{-2}.h^{-1}	SAD_m[b]	0.30
SEC, biological aeration, kWh.Nm^{-3} air	$E'_{A,bio}$	Calculated (Table 2)
SEC, biological aeration, kWh.m^{-3} permeate	$E_{A,bio}$	Calculated (Table 2)
SEC, membrane aeration, kWh.Nm^{-3} air	$E'_{A,m}$[c]	Calculated (Table 2)
SEC, membrane aeration, kWh.m^{-3} permeate	$E_{A,m}$[d]	Calculated (Table 2)
SEC, permeate pumping, kWh.m^{-3} permeate	$E_{L,p}$[e]	Calculated (Table 2)
SEC, sludge pumping, kWh.m^{-3}	$E_{L,s}$[f]	0.016.R
Transmembrane pressure, bar	TMP	0.3
Total pumping electrical energy efficiency, -	ε_{tot}	60% (air), 70% (sludge)
Waste sludge disposal costs, \$.teDS^{-1}	L'_{DS}	100

[a]Based on the stated fixed interval (maintenance) cleaning schedule. [b]SAD Specific aeration demand ([a]ir flow rate/membrane area for air scour), mean value from Judd (2011); SEC specific energy consumption, kW per m^3 permeate; [c]Blower power/air flow rate; [d]Blower power/permeate flow rate; [e]Pump power/permeate flow rate; [f]Pump power/sludge flow rate. Underscored parameter values dependent on Scenario.

Table 2. OPEX-related equations (adapted from Judd, 2017)

Parameter	Symbol	Equation
<u>Membrane</u>		
SEC, total[a], kWh.m^{-3}	E_m	$E'_{A,m}SAD_m/J + E_{L,s}R + E_{L,m}$
SEC, permeation, kWh.m^{-3}	$E_{L,m}$	$TMP/(36\ \varepsilon_{tot})$
<u>Process biology (assuming MLE process denitrification)</u>		
Oxygen demand, kg.m^{-3}	D_{O2}	$\Delta S_{COD}\,(1-\lambda_{COD}Y_{obs} - 1.71\lambda_{TKN}Y_{obs}) + 1.71\Delta S_{TKN} - 2.86\Delta S_{Nitrate}$
SAD, Nm^3.m^{-2}.h^{-1}	SAD_{bio}	$D_{O2}/(\rho_A\, C'_A\ \mathrm{OTE}\ y\ \alpha\ \beta\ \gamma).Q_F\ =\ Q_{A,bio}/Q_F$
SEC, aeration[b], kWh.Nm^3	E'_A	$k\,((0.0987h+1)^{0.283}-1)/\varepsilon_{tot}$ where k = 0.103 kWh.Nm^{-3}
SEC, permeation, kWh.m^{-3}	$E_{A,bio}$	$E'_{A,bio}\ SAD_{bio}$
<u>Waste sludge disposal</u>		
Cost, waste disposal, \$.m^{-3} permeate	L_W	Y_{obs} COD $L'_{DS}/10^6$
<u>OPEX</u>		
Cost m^{-3} permeate, \$.m^{-3}	L_O	$L_E\,(E_m + E_{A,bio}) + L_M/(J\,t) + L_C + L_W + L_L$

[a]J takes units of m^3 per m^2 per h. [b]Energy demand per unit volume (Nm^3) of air for membrane air scour ($E'_{A,m}$) or process biology aeration ($E'_{A,bio}$). All symbols as defined in Table 1.

Table 3. Scenarios and key parameter values

Scenario		Q m³/d	COD mg/L	J LMH	t h
1	Medium municipal works	10,000	500	20	70080
2	Large municipal works	100,000	500	20	70080
3	Small industrial works	1,000	5000	15	52560
4	Large industrial works	10,000	5000	15	52560

All other values as given in Table 1

Results and discussion

Data processing

α-factor correlations

α-factor trends with sludge concentration have tended to take the form of either a linear (Kim et al, 2019; Henkel et al, 2011) or exponential (Xu et al, 2017; Germain et al, 2007; Rosenberger et al, 2003) decline with the MLSS (mixed liquor suspended solids, X) or MLVSS (mixed liquor volatile suspended solids, X') concentration. As has been widely acknowledged (Henkel et al, 2011), there is little consistency between the various correlations generated between α and X (Fig. 1). Within the range of MLSS concentration appropriate to the MBR process tank (6-12 g/L), the averaged α-factor trend for $X > 6$ g/L (where $\alpha \sim 1$ at $X < 6$) is:

$$\alpha = 1.72e^{-0.094X} \quad [1]$$

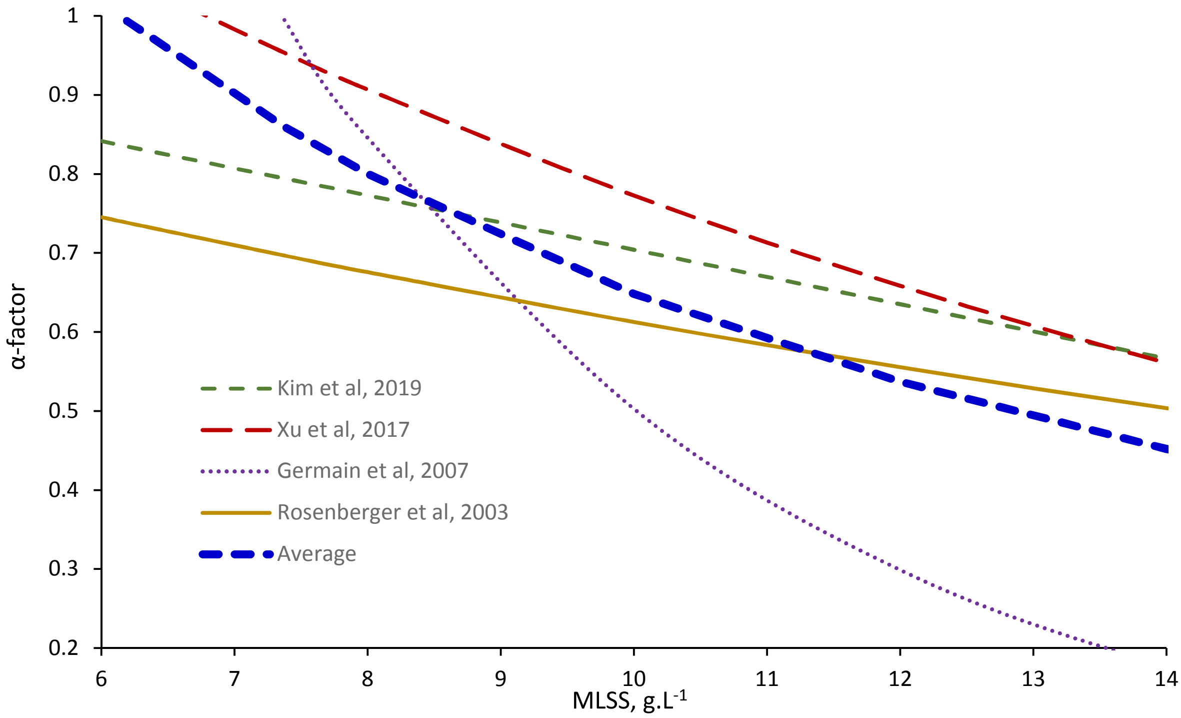

Figure 1: Published alpha factor trends

Feedwater quality and purification

Trends in COD removal with concentration for the four industrial effluent types suggest that for all types other than landfill leachate, removal is in the 90-99% range above feed concentrations of 1000 mg/L (Fig. 2). The % removal trend sharply declines below 1000 mg/L feed COD for the textile and petroleum effluent data. Although all three data sets (i.e. food &

beverage, petroleum and textile effluents) are highly scattered, a roughly logarithmic function can be used to define % removal up to a concentrations of ~4000 mg/L COD. Beyond this threshold COD removal appears to be in the 97-99% range for these effluents. At feed COD concentrations of 200-6000 mg/L the mean COD removals for food & beverage, textile and petroleum effluents are 97.2 ± 2.0%, 92.6 ± 5.0% and 90.7 ± 5.9% respectively (Fig. 3a).

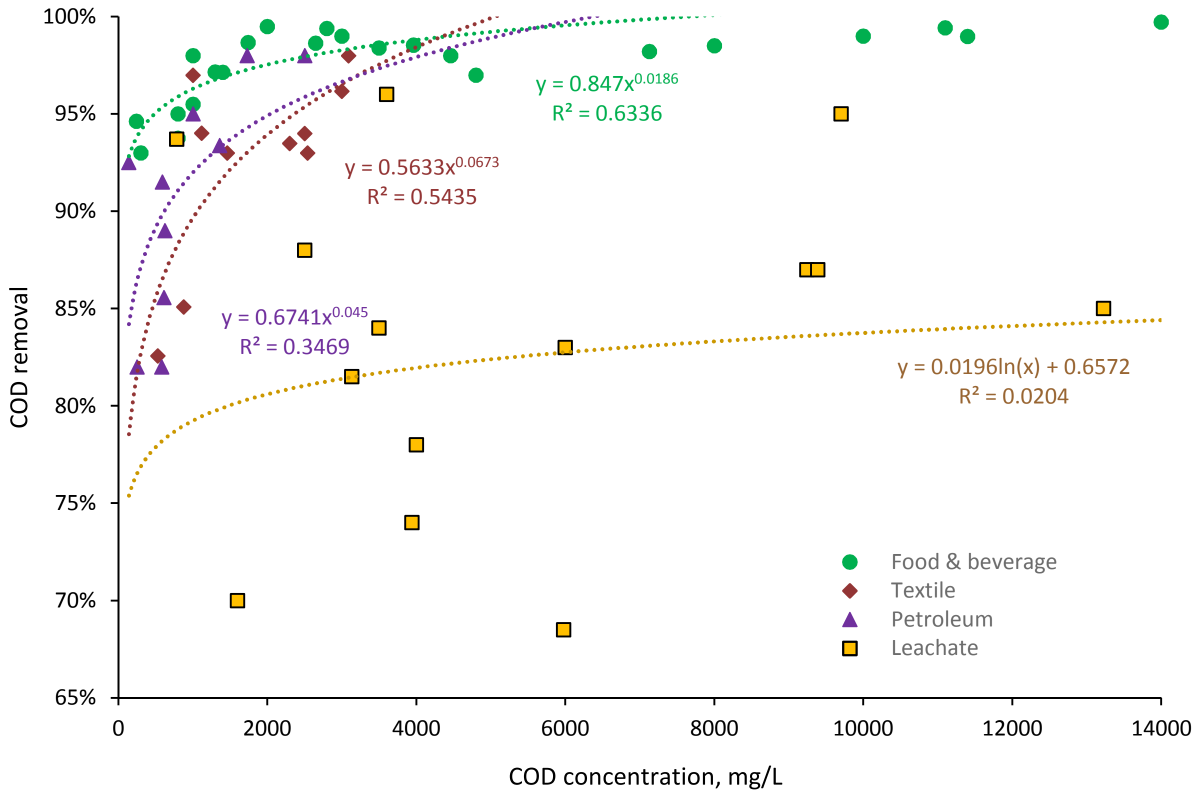

Figure 2: COD removal as a function of feedwater concentration for four different industrial effluent types (see *Additional Information* for data sources)

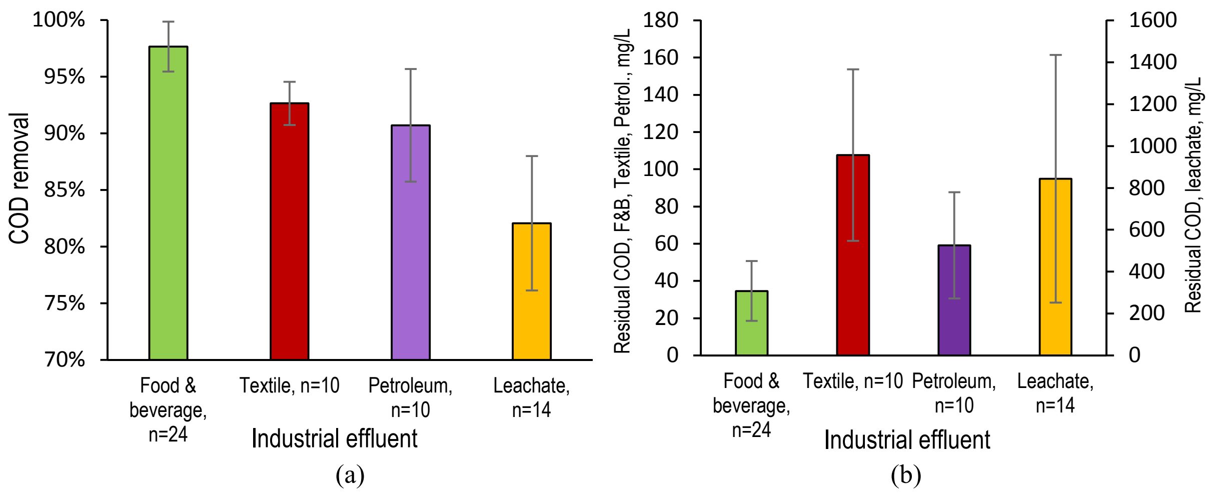

Figure 3: Averaged data for (a) COD removal and (b) permeate COD levels for the four effluent types. Data for the textile and petroleum effluents refer to COD feed concentrations below 3,100 mg/L.

In the case of landfill leachate mean removals are much lower and very highly scattered at 82.0% ± 10.2% (Fig. 3a), with no evident trend with feed COD concentration (Fig. 2). This results in considerably higher COD levels in the permeate (Fig. 3b) – more than 20 times that of food & beverage effluent over the same of COD feed concentration range (200-14,000 mg/L). It is well known (Hashisho & Fidel, 2016; Alvarez et al, 2004) that landfill leachate treatability varies with its age, with old leachates being generally more biorefractory than younger ones. However, a consideration of COD removal with BOD/COD ratio, based on available landfill leachate data (Fig. 4), again indicates very significant data scatter with removals ranging from 68 to 96% at BOD/COD ratios below 0.2.

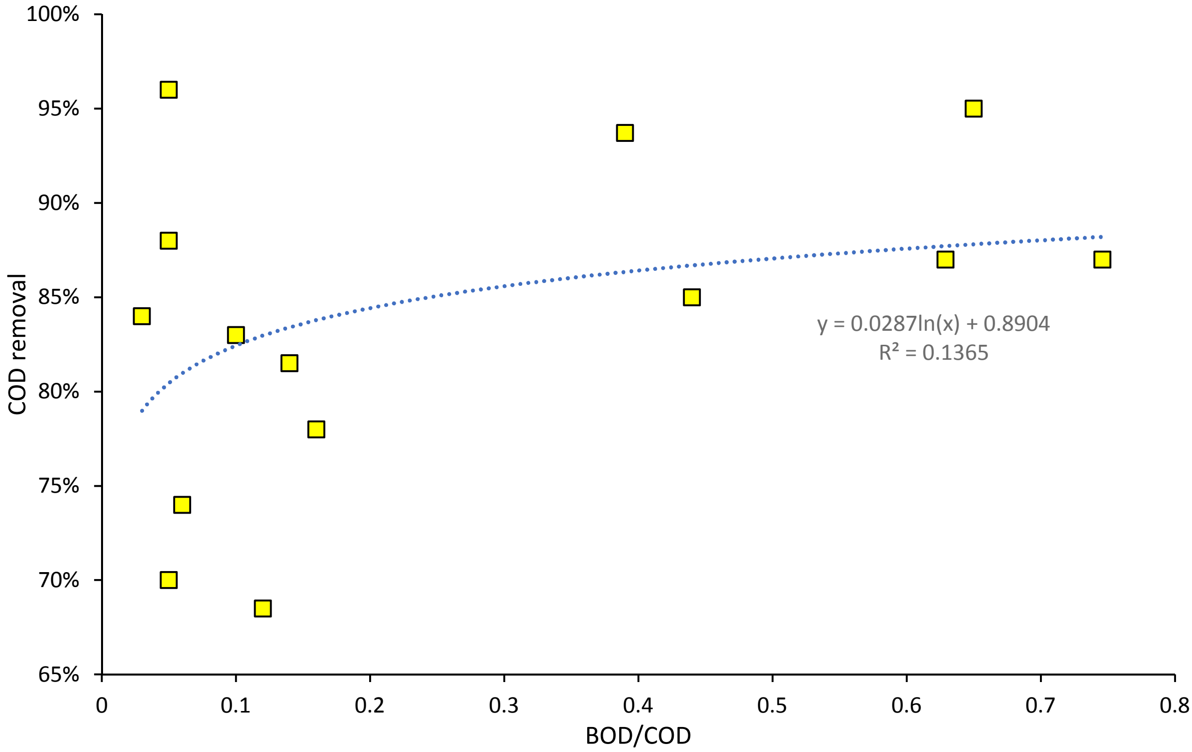

Figure 4: COD removal as a function of feedwater BOD/COD ratio, landfill leachate data

For the purposes of the OPEX calculations, the COD removal was based on a food effluent source for the industrial effluent scenarios. These effluents are generally low in TKN (Judd, 2014; Lin et al, 2012). A COD concentration of 2000 mg.L^{-1} was assumed based on a pre-clarified effluent at high COD concentrations, with clarification normally achieved using dissolved air flotation, and a TKN:COD mass ratio of 0.01. At this concentration COD removal is around 97-98% (Fig. 2). For the municipal effluent the feed COD concentration was taken as 500 mg.L^{-1} and the TKN:COD ratio as 0.1, representative of a medium-strength sewage (Tchobanoglous et al, 2003), and the %COD removal taken as 95%. This is comparable to that of food & beverage wastewater at the same feed concentration (Judd, 2011, 2014).

Operation and maintenance

For an immersed MBR the key operating parameters are the flux and membrane air scour, the latter quantified as the specific aeration demand with respect to the membrane area (SAD_m) in Nm^3.h^{-1} per m^2 membrane area. Whereas SAD_m does not in principle change with feedwater type, and has been reported to be ~0.30 ± 0.11 Nm^3.h^{-1}.m^2 for an immersed hollow fibre (HF) MBR (Judd, 2011), the flux is usually significantly lower for most industrial effluents compared with municipal ones (Fig. 5). The current analysis assumed values of 15 and 20 LMH for the industrial and municipal effluents respectively, based on the mean values across data sets of n

= 12 and 24 respectively taken from published studies. The flux does not apparently change with immersed membrane configuration, i.e. between flat sheet and hollow fibre, according to Judd (2011). The impact of both flux and air scour are considered as part of the sensitivity analysis.

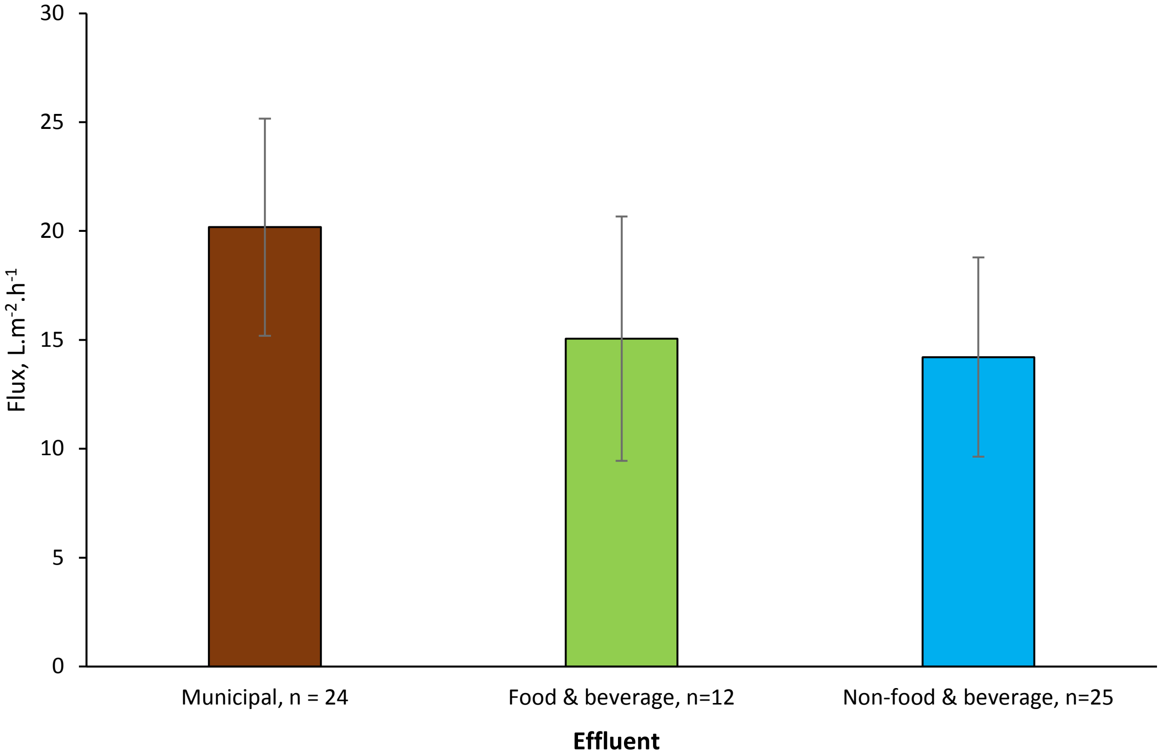

Figure 5: Mean net flux values reported for municipal and industrial MBRs.

Labour costs

Based on the 20 data points from the three different sources, the FTE per unit flow follows an approximate power law relationship with flow (Fig. 6):

$$FTE\ per\ 1000\ m^3 d^{-1} = 59.3Q^{-0.507} \quad [2]$$

According to this data set, the labour effort ranges from >3 FTE.m^{-3} at low flows to <0.2 at flows above 100,000 m^3.d^{-1}. An operator rate of \$25 per FTE-h, or \$200 FTE-d^{-1}, including overheads was assumed in the current analysis.

Computed OPEX trends

The distribution of OPEX between the five cost contributors indicates the labour costs to be the most consistently significant factor for all the scenarios considered, other than for the large municipal plant of Scenario 2 (Fig. 7). At the very large flow (100,000 m^3/d) considered for this case, the labour costs are around 25% lower than the energy cost. For the benchmark case of a medium-sized municipal works (Scenario 1, 10,000 m^3/d capacity), labour costs contribute 50% of the total OPEX (Fig 7). At the low flows of the small industrial effluent plant the labour costs represent 61% of the total.

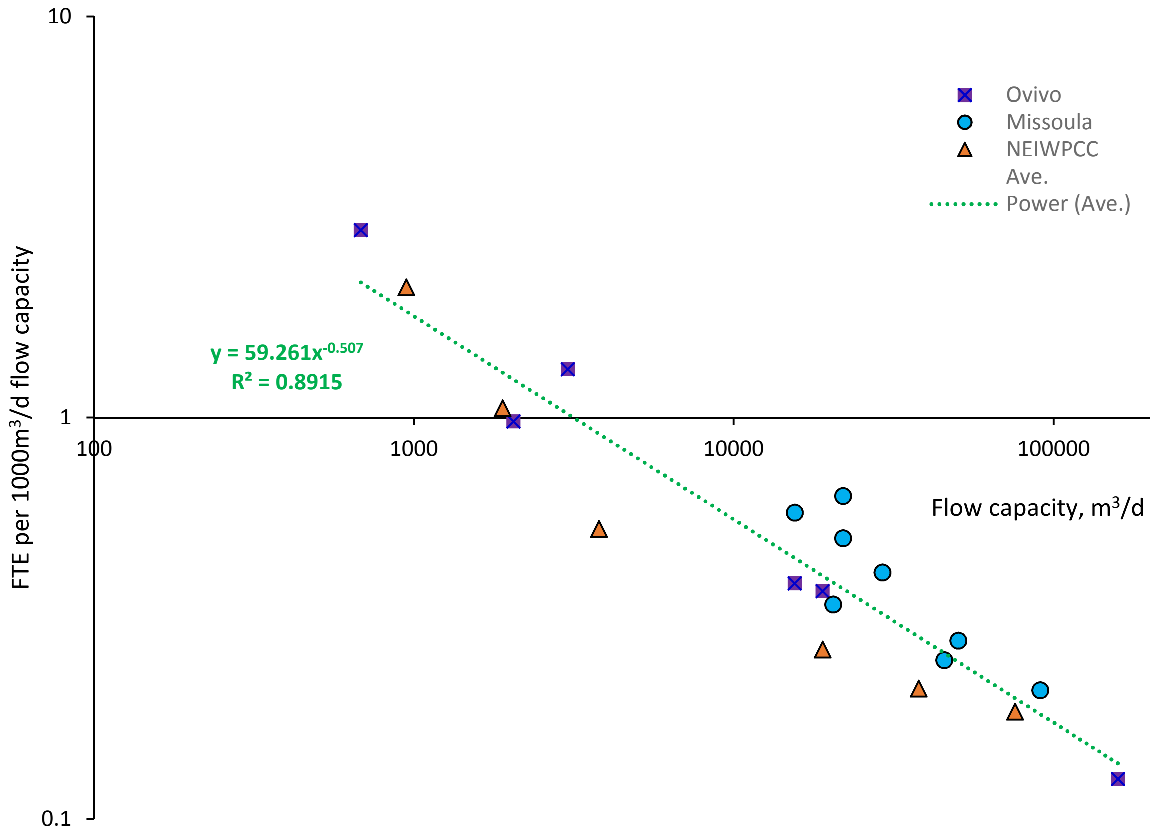

Figure 6: Labour effort as FTE per 1000 m^3/d flow vs. plant flow capacity

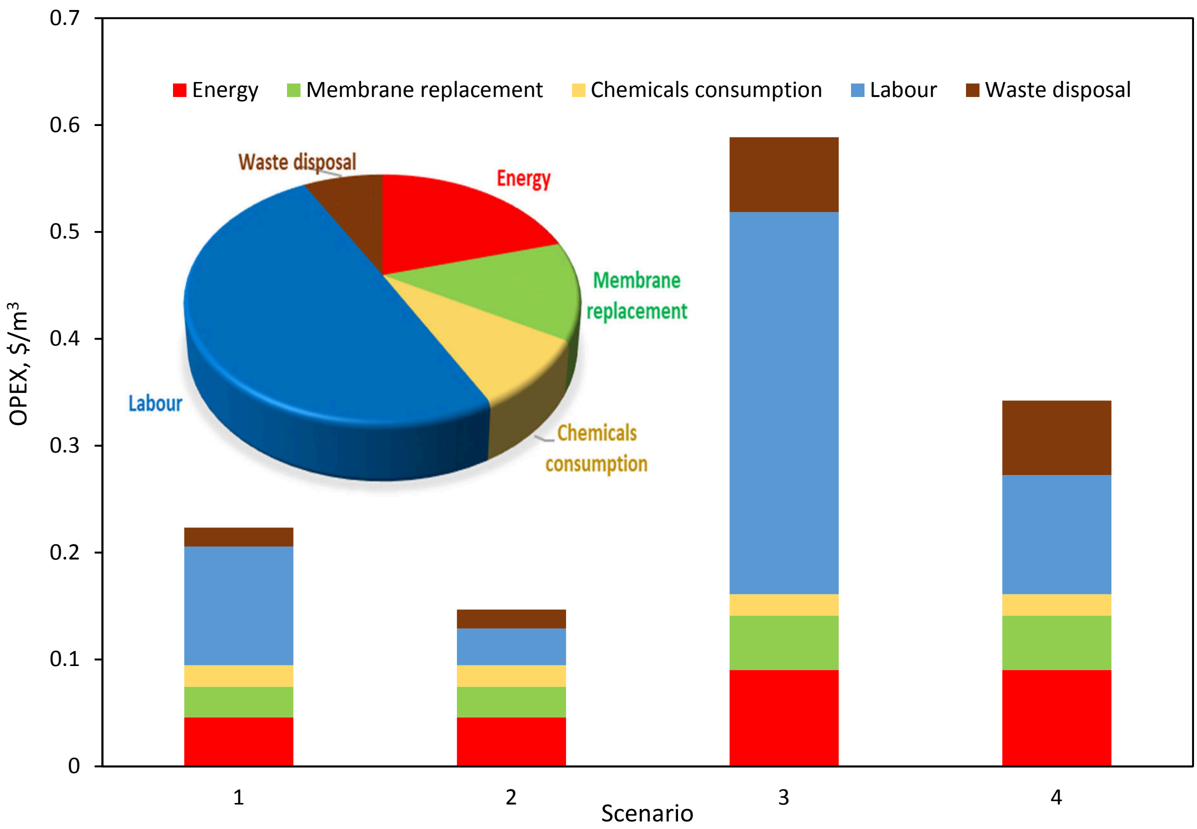

Figure 7: OPEX contributions for the four scenarios considered (see Table 3: 1 Medium municipal works, 2 Large municipal works, 3 Small industrial works, 4 Large industrial works). Inset shows distribution for Scenario 1.

Whilst labour costs are often ignored in OPEX analysis, the few which have included it have indicated a wide variation in its contribution to overall costs, from as little as 13% (DeCarolis et al, 2007) to as much as 70% (Cashman and Mosely, 2016) for a 19,000 $m^3.d^{-1}$ MLD municipal WwTW. In the exhaustive analysis conducted by Young et al (2013), also for a 19,000 $m^3.d^{-1}$ capacity plant, labour costs (based on 7 FTE staff effort in their case) were calculated to contribute 44% of the OPEX. This is very close to the figure of 42% computed for the same flow capacity using the approach of the current study, where the corresponding labour effort from Equation 2 is 7.5 FTE. However, as pointed out by Young et al, labour costs vary widely regionally: the \$25 h^{-1} rate used in the current analysis would be considered low in most regions of Western Europe, the US and Japan and high in the Philippines, Central Africa and the Indian sub-continent.

A consideration of the sensitivity of the total cost to the 12 individual parameters for each of the four scenarios indicates, as expected, the labour cost to be the most significant of the factors considered other than for the large municipal plant (Fig. 8), where flux and energy cost are more significant factors, and large industrial plant where the COD concentration is more significant. COD concentration impacts on both the biological energy demand and waste sludge generation, the impact being proportionally larger for larger plants where the flow-normalised labour costs are lower.

Following labour costs, the most consistently significant factor across all scenarios considered is the flux. Flux (J) takes an inverse relationship with both the air:permeate ratio ($SAD_p = SAD_m/J$) and the membrane replacement frequency ($f_m = L_M/(J\ t)$), and so has a greater impact than either membrane life (t) or specific aeration demand (SAD_m) alone. None-the-less, for small to medium-sized plants its impact is less significant than that of labour effort.

The analysis provides a graphic demonstration of the widely-recognised trade-off between OPEX and CAPEX. The most direct way of reducing labour costs is by reducing the staff effort. Ignoring discounting and inflation – or else assuming the two to be approximately equal - a halving of the mean staff effort for a 1,000 m^3/d plant would save around \$0.8-0.9m over a 20-year plant life based on the assumptions used in the current study. This is in the region of 12-20% of the CAPEX for a typical municipal iMBR plant CAPEX (Cashman and Mosely, 2016; Young et al, 2013).

It should finally be acknowledged that MBR technology is expected to achieve the ultimate treatment goal with respect to treated water quality, allowing discharge or possibly reuse of the treated effluent. Whilst this appears attainable for municipal and food & beverage effluents, as well as the petroleum and textile effluents featured in this analysis, landfill leachate is much more vagarious in terms of its treatability. Downstream polishing of the MBR permeate would be required in many cases for this effluent type, adding to the OPEX.

Conclusions

The treatability of four different industrial effluent types (food & beverage, textile, petroleum and landfill leachate) by a membrane bioreactor (MBR) has been assessed with reference to the %COD removal vs. the feedwater COD concentration. The operating expenditure (OPEX) associated with the treatment of a food & beverage industrial effluent has subsequently been computed and compared with that of municipal wastewater treatment. Both the treatability and OPEX trends generated were based on published data.

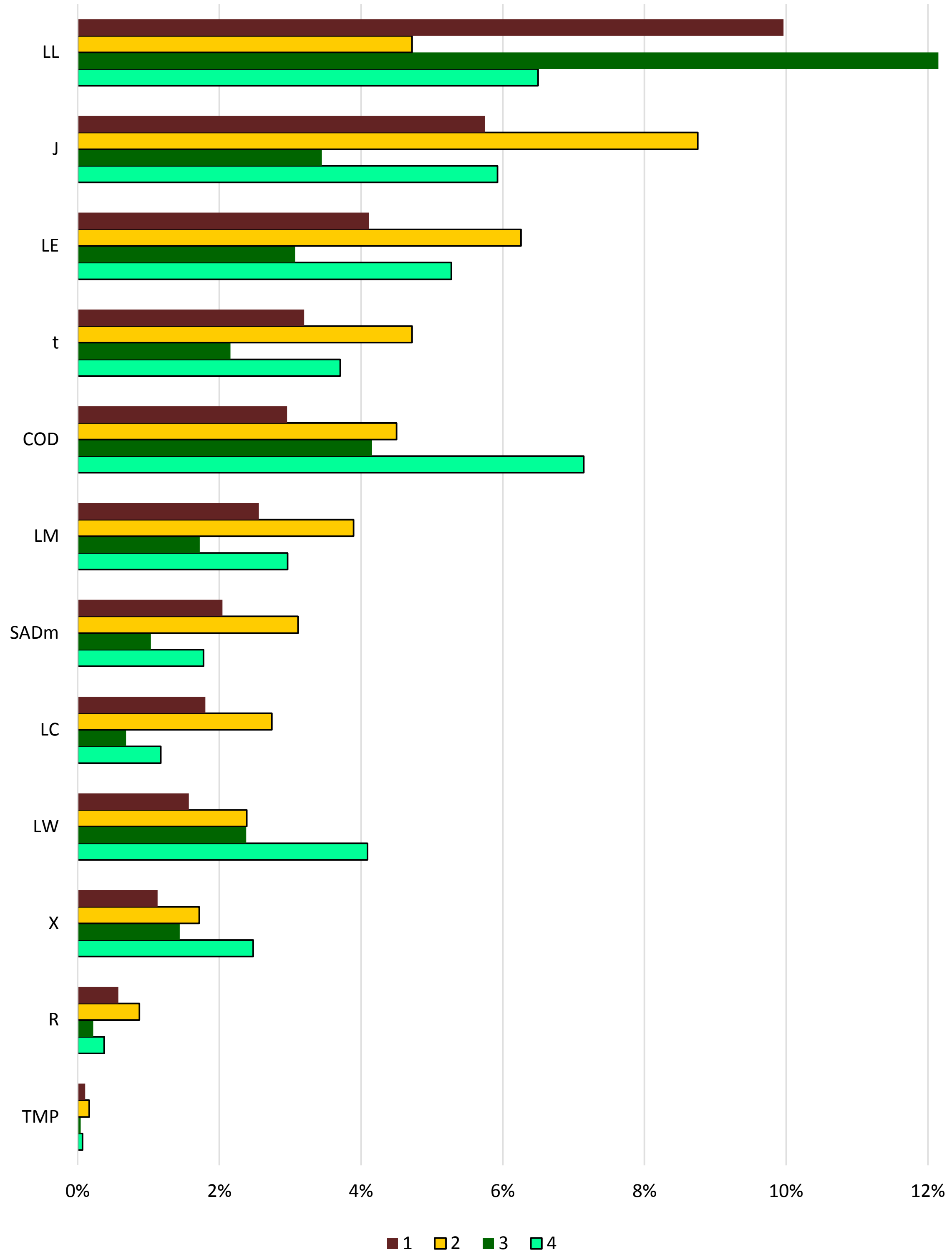

Figure 8: %change in total OPEX across Scenarios 1-4 for a 20% change in labour cost (L_L), flux (J), electrical energy cost (L_E), membrane life (t), feed COD, membrane cost (L_M), specific aeration demand (SAD_m), chemicals cost (L_C), waste disposal cost (L_W), MLSS concentration (X), recirculation ratio (R), and transmembrane pressure (TMP). Scenarios considered as given in Table 3.

Results for the three generic wastewater types indicated %COD removal to follow a roughly logarithmic trend with COD concentration up to a threshold of around 4000 mg/L COD, albeit with significant data scatter (R^2 = 0.36 – 0.54), for three of the four effluent types. Above a threshold feed COD of around 4,000 mg/L the COD removal was 97-98% for these effluents (food & beverage, petroleum and textile). For the landfill leachate the data was highly scattered and overall removal much lower, resulting in permeate COD levels more than 20 times those associated with food & beverage treatment over the same feed COD concentration range.

The OPEX determination revealed labour costs to contribute more significantly than any other of the 12 parameters computed for three of the four scenarios considered (small and large industrial effluent treatment plant and the medium-sized municipal wastewater works), the exception being large municipal works where flux had the greatest impact. An outline full cost analysis suggested that a halving of the mean staff effort for a 1,000 m^3/d plant would save around $0.8-0.9m over a 20-year plant life, equating to 12-20% of the plant investment costs. This outcome suggests that it is likely to be cost effective to invest in items such as automated process control and pretreatment – the latter being widely identified by practitioners as being the pinch point in MBR design – to reduce labour effort over the plant life.

Acknowledgements

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