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Filtration process cost in submerged anaerobic membrane bioreactors (AnMBRs) for urban wastewater treatment

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Abstract

The objective of this study was to evaluate the effect of the main factors affecting the cost of the filtration process in submerged anaerobic membrane bioreactors (AnMBRs) for urban wastewater (UWW) treatment. Experimental data for *CAPEX*/*OPEX* calculations was obtained in an AnMBR system featuring industrial-scale hollow-fibre (HF) membranes. Results showed that operating at J_{20} slightly higher than the critical flux results in minimum *CAPEX*/*OPEX*. The minimum filtration process cost ranged from €0.03 to €0.12 per m^3, mainly depending on SGD_m (from 0.05 to 0.3 $m^3 \cdot h^{-1} \cdot m^{-2}$) and *MLSS* (from 5 to 25 $g \cdot L^{-1}$). The optimal SGD_m resulted in approx. 0.1 $m^3 \cdot h^{-1} \cdot m^{-2}$.

Keywords

Submerged anaerobic MBR (AnMBR); *CAPEX*/*OPEX*; industrial-scale hollow-fibre membranes; urban wastewater (UWW)

1. Introduction

Recent studies (see, for instance, [1, 2, 3]) have reported the need to address future research efforts on submerged anaerobic membrane bioreactors (AnMBRs) for urban wastewater (UWW) treatment towards sustainable full-scale implementation and operation. Specifically, it is required to establish adequate filtration strategies from an economical point of view, accounting not only for power requirements but also for investment, maintenance, and replacement costs. Gas sparging intensity for membrane scouring (commonly measured as specific gas demand per square metre of membrane area: SGD_m), mixed liquor suspended solids (*MLSS*) concentration and 20 ºC-standardised transmembrane flux (J_{20}) are key operating parameters that must be optimised in order to minimise capital and operating expenses (*CAPEX*/*OPEX*) in AnMBR systems [4,5,6].

The objective of this study was to evaluate the effect of the main factors affecting the filtration process cost in AnMBR technology for UWW treatment. To this aim, *CAPEX*/*OPEX* related to filtration were evaluated at different levels of SGD_m, J_{20} and *MLSS*. In order to obtain adequate results that can be extrapolated to full-scale plants, experimental data used in this study were obtained in an AnMBR system featuring industrial-scale hollow-fibre (HF) membrane units that was fed with the effluent from the pre-treatment of the Carraixet WWTP (Valencia, Spain).

2. Materials and methods

In order to assess the effect of the main factors affecting the design and operation of the filtration process in AnMBR technology for UWW, *CAPEX*/*OPEX* were evaluated at different levels of SGD_m (from 0.05 to 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$), J_{20} (varying from 80 to 120% of the experimentally determined 20 ºC-standardised critical flux: J_{C20}) and *MLSS* (from 5 to 25 $g \cdot L^{-1}$).

2.1. AnMBR plant description

Experimental data required for calculating *CAPEX*/*OPEX* were obtained in an AnMBR system that was fed with the effluent from the pre-treatment of the Carraixet WWTP (Valencia, Spain). It mainly consists of an anaerobic reactor with a total volume of 1.3 m^3 connected to two membrane tanks each one with a total volume of 0.8 m^3. Each membrane tank includes one ultrafiltration hollow-fibre membrane commercial system (PURON®, Koch Membrane Systems, 0.05 µm pore size, 30 m^2 total filtering area). Further details on this AnMBR can be found in Giménez et al. [7] and Robles et al. [8].

2.2. CAPEX/OPEX calculation

Figure 1 shows the methodology used in this study for calculating *CAPEX*/*OPEX* in AnMBRs treating UWW. This methodology was extracted from the design methodology proposed in Ferrer et al. [3]. The terms considered for *CAPEX* calculation were: acquisition of ultrafiltration hollow-fibre membranes, equipment acquisition (blowers, pumps and pipes) and reinforced concrete structures. The terms considered for *OPEX* calculation were: membrane scouring by gas sparging, permeate pumping, chemical reagent consumption for membrane recovery, membrane replacement at the end of membrane lifetime, and equipment reposition (blowers, pumps and pipes). The total annualised equivalent cost (*TAEC*) was calculated by adding the annualised

CAPEX to the annual *OPEX*. Unit costs and further details about the LCC methodology can be found in Table 1 as well as in Ferrer et al. [3].

3. Results and discussion

3.1. Effect of MLSS on filtration process cost

Figure 2 illustrates the effect of *MLSS* on *TAEC* when operating at different levels of SGD_m (from 0.05 to 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$) and J_{20} ranging below and above the critical filtration region (from 80 to 120 % of J_{C20}). Specifically, this figure shows the resulting *TAEC* when operating at *MLSS* of 5 (Figure 2a), 15 (Figure 2b) and 25 $g \cdot L^{-1}$ (Figure 2c).

As Figure 2 shows, increasing *MLSS* from 5 to 25 $g \cdot L^{-1}$ considerably increases *TAEC* (up to 91%) for a given SGD_m level, mainly due to increasing *CAPEX*. This *CAPEX* increase is related to the reduction in J_{C20} as *MLSS* increases (for a given SGD_m), which results in a subsequent increase in the required membrane area. On the other hand, increasing *MLSS* from 5 to 25 $g \cdot L^{-1}$ considerably increases *TAEC* (up to 82%) for a given J_{20} due to increasing *OPEX*. This *OPEX* increase is related to the necessity of increasing SGD_m as *MLSS* increases in order to maintain sustainable membrane fouling propensities, which results in a consequent increase in the cost of membrane scouring by gas sparging.

High operating *MLSS* concentrations could be reached when operating at high sludge retention times (*SRTs*), which may be required when running AnMBR technology at low temperatures (i.e. psychrophilic temperature conditions) in order to achieve proper organic matter removal rates. As can be seen in Figure 2, high *MLSS* concentrations would result in an increase in *TAEC* mainly caused by an increase in the gas sparging intensity for membrane scouring and/or the required membrane area. Nevertheless, this drawback can be avoided by increasing the volume of the anaerobic reactor thus reducing the operating *MLSS* level for a given *SRT*. Hence, it is required to optimise not only the filtration process cost but also the biological process cost (i.e. reactor volume) in order to optimise the design and operation of AnMBR technology for UWW treatment (see [3]).

3.2. Effect of J_{20} on filtration process cost

Figure 2 also illustrates the effect of the operating J_{20} on *TAEC* at different levels of SGD_m (from 0.05 to 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$) and *MLSS* (5, 15 and 25 $g \cdot L^{-1}$). As Figure 2 shows, there is an optimal operating J_{20} that results in minimum *TAEC* for any combination of SGD_m and *MLSS*. Specifically, for SGD_m from 0.05 to 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$, the optimal operating J_{20} determined in this study ranged around 5-15, 15-25, and 25-35 LMH when operating at 25, 15 and 5 $g \cdot L^{-1}$ of *MLSS*, respectively. This optimal operating J_{20} corresponds to a J_{20} slightly higher than the experimentally determined J_{C20} (around 100-110% of the J_{C20}).

By way of example, Table 2 illustrates the effect of selecting a J_{20} value below and above the critical filtration region (80, 100 and 120% of the J_{C20}) on *TAEC*. Results in Table 2 were determined at 15 $g \cdot L^{-1}$ of *MLSS* and SGD_m of 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$. As this table shows, operating at J_{20} above J_{C20} reduces both investment (i.e. decreases the required membrane filtration area) and membrane scouring costs (i.e. increases the net permeate flow per membrane area whilst maintaining SGD_m). However, operating at J_{20} above J_{C20} increases chemical cleaning frequency, increasing therefore chemical reagent consumption whilst decreasing membrane lifetime (i.e. increases membrane replacement cost). A considerable increase in *TAEC* is observed when operating at J_{20} above the upper boundary of the critical filtration region (approx. for J_{20} values above 110 % of the J_{C20}). Therefore, since membrane replacement is a key factor affecting the total cost of the filtration process, considerable attention should be paid to the optimisation of membrane lifetime by operating under a sustainable regime. Indeed, the optimal operating J_{20} determined in this study corresponded to the maximum J_{20} for which membrane replacement was not required.

3.3 Effect of SGD_m on filtration process cost

Figure 2 also illustrates the effect of SGD_m on *TAEC* when operating at different levels of *MLSS* (5, 15 and 25 $g \cdot L^{-1}$) and J_{20} ranging below and above the critical filtration region (from 80 to 120 % of J_{C20}). As shown in Figure 2, for J_{20} around 80-95%, at every *MLSS*, the minimum *TAEC* corresponded to a low SGD_m level, around 0.05-0.10 $m^3 \cdot m^{-2} \cdot h^{-1}$. However, considering a J_{20} around 115-120% of J_{C20}, the optimal SGD_m value was around 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$. As commented before, the optimal J_{20} is reached when operating at J_{20} of approx. 100-110% of J_{C20}. Figure 3 illustrates the effect of SGD_m on *TAEC* when operating at different *MLSS* (from 5 to 25 $g \cdot L^{-1}$) for the optimal J_{20} ($J_{20\ optimal}$) determined from the results shown in Figure 2. The results shown in Figure 3 reveal that, in this study, the optimal SGD_m value which results in minimum *TAEC* was around 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$ for every *MLSS* level.

Hence, the results shown in this study revealed that decreasing SGD_m below 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$ increases *TAEC* due to increasing membrane fouling propensity (i.e. low shear intensities were applied on the membrane surface), which increases membrane chemical cleaning requirements and reduces membrane lifetime. On the other hand, increasing SGD_m above 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$ allows reducing the costs related to membrane maintenance (i.e. it allows reducing membrane fouling propensity) and/or investment (i.e. it allows increasing $J_{20\ optimal}$). Nonetheless, the higher cost related to membrane scouring by gas sparging offsets these possible savings thus resulting in an increase in *TAEC*.

3.4. Optimum design and operation of filtration in AnMBR technology for UWW treatment

As commented above, Figure 3 shows the optimal J_{20} and *TAEC* calculated in this study for SGD_m from 0.05 to 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$ and *MLSS* from 5 to 25 $g \cdot L^{-1}$. As previously commented, $J_{20\ optimal}$ corresponded to a J_{20} value slightly higher than J_{C20}, whilst the optimal SGD_m resulted in values around 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$ (see Figure 3). The optimum *TAEC* estimated in this study ranged from €0.03 to €0.12 per m^3 of treated water. In this respect, a significant part of the operation cost therefore arises from the balance between SGDm, and the net permeate flux flowing through it. The ratio of these two quantities yields a unitless parameter called the specific gas demands per permeate volume (SGD_P). Therefore, operating at high J_{20} and/or low SGD_m (i.e. low SGD_P) reduces considerably the membrane capacity required and/or the energy requirements. Specifically, the optimum specific gas demands per permeate volume (SGD_P) in this study resulted in the range from 4 to 11, depending on the MLSS concentration. According to Judd [12], in most full-scale immersed MBR installations currently in operation, specific air demands per permeate volume (SADp) on average exceeds 10, and can be as high as 50 at some sites. As SADp relates directly to the cost of aeration energy for membranes, it is desirable to reduce SADp so as to reduce operational cost for MBRs.

Table 3 shows the energy consumption and total cost of different full-scale MBR assessed. For instance, Verrecht et al. [14], carried out a cost analysis for a full-scale HF MBR, showing a variation in SADp values from 15 to 25, with filtration cost values of 3.8 and 3.48 € per m^3 when operating at 15 to 30 LMH, respectively. Hence, it can be concluded that from an economic perspective, AnMBR may be a promising sustainable wastewater technology in comparison with other existing urban WWT technologies, such as MBR technology.

On the other hand, Figure 3 shows how *TAEC* decreases as *MLSS* decreases. For instance, the optimum *TAEC* decreases from €0.10 to €0.03 per m^3 of treated water when decreasing *MLSS* from 25 to 5 $g \cdot L^{-1}$, respectively, at SGD_m of 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$. Thus, it seems to be obvious that the optimum design and operation of the filtration process in AnMBR technology for UWW treatment is achieved when operating membranes at the lowest allowable *MLSS* concentration. However, as previously commented, decreasing *MLSS* means increasing the volume of the anaerobic reactor for a given *SRT*. According to Ferrer et al. [3], it is required to optimise not only the filtration process but also the biological process (i.e. reactor volume) in order to optimise the cost of AnMBR technology for UWW treatment. Nonetheless, the results shown in this study highlight the necessity of optimising design and operation of filtration in order to improve the feasibility of AnMBR technology to treat UWW since selecting adequate combinations of J_{20}, SGD_m and *MLSS* considerably reduces *TAEC*.

3.5. Effect of membrane and energy costs on filtration process cost

A future decrease in the membrane acquisition cost (or selecting more economical membrane types or suppliers) may reduce the effect of this term on the design and operation of AnMBR technology. However, nowadays membrane acquisition cost represents a great weight in the total filtration cost of AnMBR technology, thus it is necessary to maximise membrane lifetime whilst minimising the required membrane area.

On the other hand, the future trends in energy cost are a determining factor for *TAEC* in AnMBR technology. A ‘worst case’ of a 10% annual increase in energy cost, corresponding to a doubling of energy prices roughly every 10 years, increases the total cost of the filtration process around 16 and 54% when operating at SGD_m of 0.05 and 0.30 $m^3 \cdot h^{-1} \cdot m^{-2}$, respectively, along the 20 years of the depreciation of the plant.

Hence, it is important to emphasise that the results shown in this study are strongly dependent on energy and membrane costs. Therefore, one key point for maximising the long-term economic feasibility of the filtration process in AnMBR technology is decreasing power requirements, whilst maximising membrane lifetime thus limiting membrane replacement cost.

4. Conclusions

The effect of the main factors (J_{20}, *MLSS*, and SGD_m) affecting the cost of the filtration process in AnMBR technology treating UWW has been assessed. The results shown in this study revealed that operating at J_{20} slightly higher than the critical flux (around 100-110% of the J_{C20}) results in minimum *TAEC*. Moreover, the results revealed that the lowest the operating *MLSS* the lowest *TAEC* related to filtration. The optimal SGD_m resulted in approx. 0.1 $m^3 \cdot h^{-1} \cdot m^{-2}$ for *MLSS* ranging from 5 to 25 $g \cdot L^{-1}$ when operating at the corresponding optimal J_{20} (around 100-110% of the J_{C20}). The optimum *TAEC* estimated in this study ranged from €0.03 to €0.12 per m^3 of treated water.

Acknowledgements

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Table and Figure captions

Table 1. Unit costs used to evaluate capital and operating expenses (CAPEX/OPEX) related to filtration in AnMBR technology treating UWW

Table 2. Effect of J_{20} on *TAEC* at SGD_m of 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$ and *MLSS* of 15 $g \cdot L^{-1}$.

Table 3. Energy consumption and total cost of different full-scale MBRs.

Figure 1. Proposed methodology for *CAPEX*/*OPEX* calculations related to filtration in AnMBR technology treating UWW (extracted from Ferrer et al., [3]).

Figure 2. Effect of J_{20} and SGD_m on *TAEC* at different levels of *MLSS:* **(a)** 5 $g \cdot L^{-1}$ **(b)** 15 $g \cdot L^{-1}$ and **(c)** 25 $g \cdot L^{-1}$.

Figure 3. Effect of $J_{20\ optimal}$, SGD_m and *MLSS* on the optimum *TAEC*.

Table 1. Unit costs used to evaluate capital and operating expenses (CAPEX/OPEX) related to filtration in AnMBR technology treating UWW

Unit costs of capital and operating expenses		Reference
Steel pipe (DN: 0.3 m)/(DN: 1.4 m), €·m-1	58/520	]9]
Concrete wall/slab, € per m	350/130	[9]
Ultrafiltration hollow-fibre membrane, (maximum chloride contact of 500,000 ppm·h cumulative), € per m2	35	PURON®, Koch Membrane Systems
Energy, € per kWh	0.138	[10]
Sodium hypochlorite, (NaOCl Cl active 5% PRS-CODEX), € per L	11	Didaciencia S.A.
Acid citric (Acid citric 1-hidrate PRS-CODEX), € per kg	23.6	Didaciencia S.A.
Blower (ELEKTROR RD 84, QB= 5400 m3·h-1; Lifetime: 50000 hours), €	5900	Elektror S.A.
Rotary Lobe pump (INOXPA, QP 140 m3·h-1)	25000	INOXPA, S.A
Land cost , €·m-2	0.97	[11]

Table 2. Effect of J_{20} on the filtration process cost at SGD_m of 0.10 $m^3 \cdot h^{-1} \cdot m^{-2}$ and $MLSS$ of 15 $g \cdot L^{-1}$.

		CAPEX		***OPEX***								***TAEC***
J₂₀		Membrane area and membrane tank		Membrane scouring		Chemical reagent consumption		Total operating cost		Membrane replacement		
LMH	% of J_{C20}	€·m^{-3}	%	€·m^{-3}	%	€·m^{-3}	%	€·m^{-3}	%	€·m^{-3}	%	€·m^{-3}
14	80	0.033	61.0	0.018	32.1	0.004	6.8	0.021	38.9	0.000	0.0	0.055
18	100	0.027	57.5	0.014	30.6	0.005	11.7	0.020	42.3	0.000	0.0	0.047
22	120	0.022	17.3	0.011	8.4	0.036	26.2	0.047	34.6	0.067	49.0	0.136

Table 3. Energy consumption and total cost of different full-scale MBRs.

Membrane configuration	**Operating conditions**	**Energy consumption, kWh·m^{-3}**	**Total cost, €·m^{-3}**	**Reference**
Submerged MBR (flat sheet)	J=19 LMH	6.06	0.49	[13]
	J=25 LMH	4.88	0.39	
MBR (HF)	J=15 LMH SADp=15.3		3.8	[14]
	J=30LMH SADp=19.1		3.48	
Submerged MBR (HF)	J=20LMH; SADm=0.3	0.9	---	[15]
Submerged MBR	J=22-34 LMH; TMP=0.2-0.6 bars; MLSS=9-12 g·L^{-1}	0.64	---	[16]
Submerged MBR (flat sheet)	J=24-40LMH	1.41	---	[17]

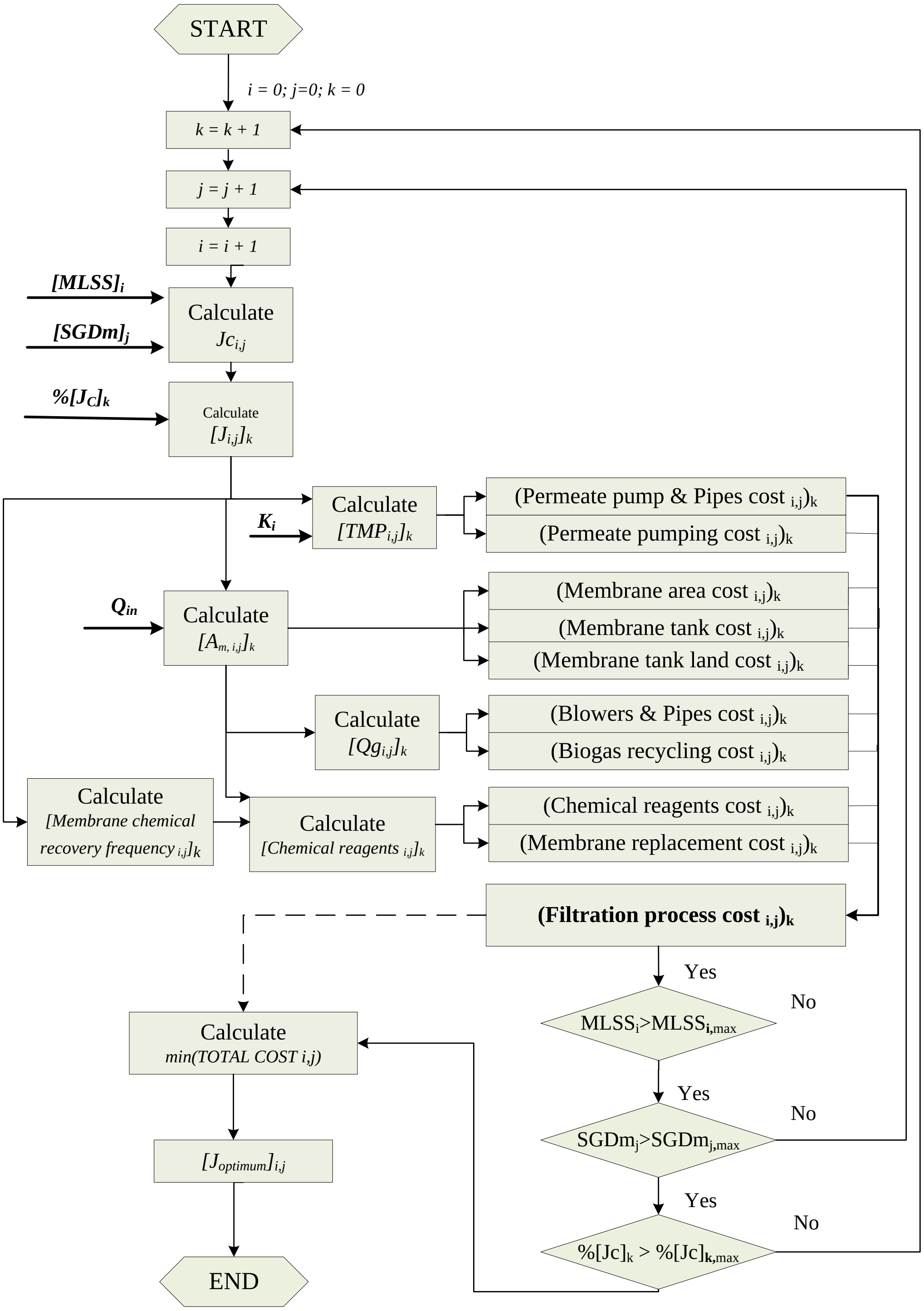
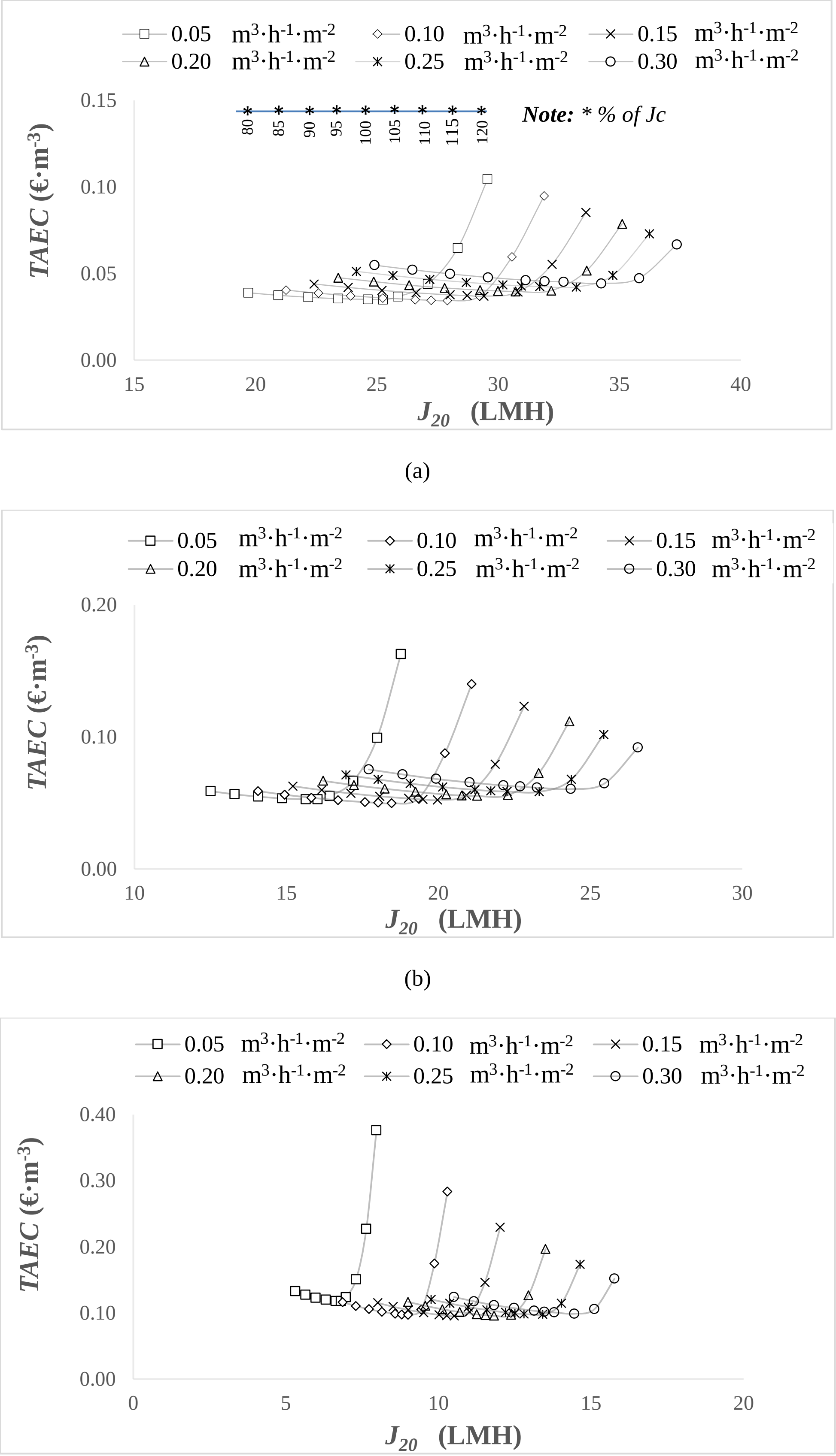


Figure 1. Proposed methodology for *CAPEX*/*OPEX* calculations related to filtration in AnMBR technology treating UWW (extracted from Ferrer et al., [3]).



(a)

(b)

(c)

Figure 2. Effect of J_{20} and SGD_m on *TAEC* at different levels of *MLSS:* **(a)** 5 g·L^{-1} **(b)** 15 g·L^{-1} and **(c)** 25 g·L^{-1}.

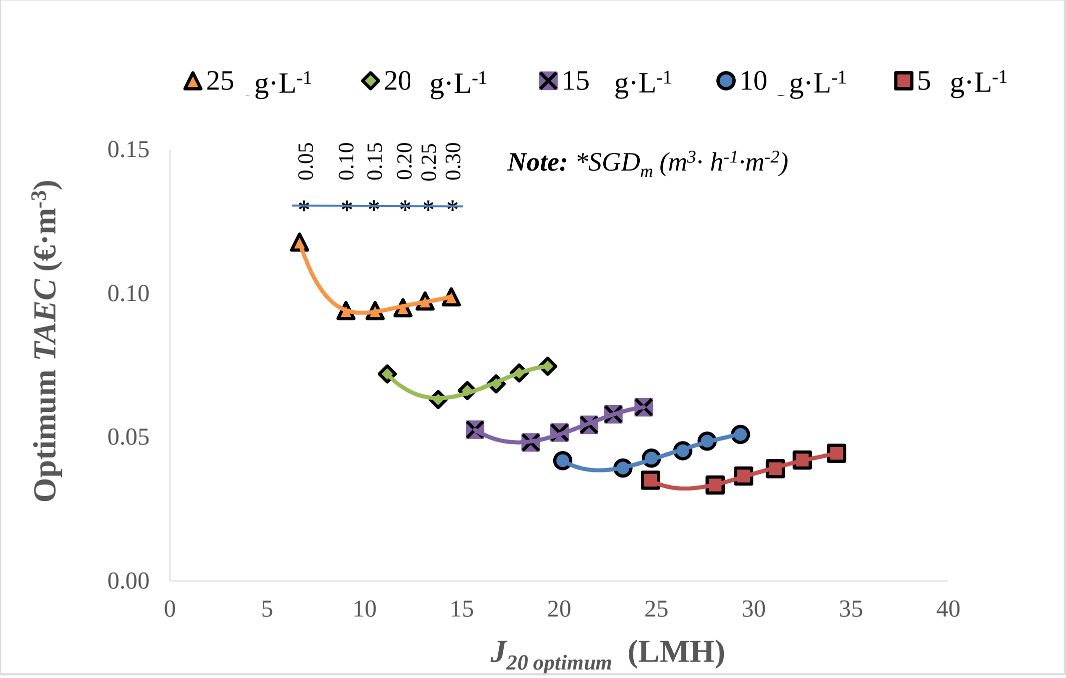


Figure 3. Effect of $J_{20\ optimal}$, SGD_m and $MLSS$ on the optimum $TAEC$.