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ScienceDirect
DESALINATION
Desalination 227 (2008) 72–84
www.elsevier.com/locate/desal

Long-term experience with an automatic process control for nitrogen removal in membrane bioreactors

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Received 12 February 2007; Accepted 25 May 2007

Abstract

The alternating processes applied in membrane bioreactors for municipal wastewater treatment may be an attractive option to reduce the energy consumptions and optimize carbon and nitrogen removal. However, the knowledge of these systems is often based on empirical results so to discourage the plant operators for its adoption. This paper discusses and compares the empirical evidence coming from two different alternating membrane bioreactors, a demonstration and a full-scale one. The two plants treat two real municipal wastewaters, rather different for both C:N ratio and degree of biodegradability of the influent organics. Nine steady-state runs have been carried out in the demonstration plant, while a one whole year operation has been considered for the full-scale system. Combining the results of the two MBRs, it was found that the alternating process was able to adjust automatically and adequately the aeration of the biological reactor with a nitrogen loading rate in the range 0.05–0.18 kgN m^{-3} d^{-1} and C:N mass ratios greater than 5–6. As a result, the use of the available carbon source, with concern to the total nitrogen removal, was as low as 0.1 kg of total nitrogen removed per kg of total influent COD. Effluent total nitrogen met the standard for reuse with specific energy consumptions in the range 85–109 $gTN_{removed}$ per $kWh_{consumed}$. Considering the usual loading conditions of the municipal wastewater treatment plants in Italy, membrane bioreactors operating alternating processes may be implemented to increase the nitrogen treatment capacity of existing plants and achieve the standards for reuse.

Keywords: Water reuse; Demonstration and full scale; Membrane bioreactor; Intermittent aeration control; Upgrading

Presented at the First Oxford and Nottingham Water and Membranes Research Event, 2–4 July 2006, Oxford, UK.

0011-9164/08/$– See front matter
doi:10.1016/j.desal.2007.05.036

1. Introduction

Membrane bioreactors (MBRs) can now be considered a reliable and widely applied technology for advanced wastewater treatment. In fact, this treatment system, which combines the activated sludge process and the separation of biomass from treated water on porous membranes, is experiencing an increasing success on markets [1–3]. In particular, MBRs allow to treat both municipal and industrial wastewaters for reclamation and reuse [4] and to attain very high quality standards for effluents [5] (i.e., conventional and priority pollutants removal). However, although the full-scale applications are increasing in number and treatment capacity, the most appropriate practice to design and operate MBRs is still not consolidated [1]. Therefore, there is a necessity to have a well understanding of the engineering principles so to allow MBRs to be successfully implemented in a range of different situations. MBR configuration is a key issue for the optimization of performance and operation and management (O&M) costs and can play a fundamental role to make management for the operators easier.

Biological removal of carbon and nutrients in MBRs can be accomplished by a number of options. Among the schemes with suspended biomass, multizone and sequencing schemes are successfully applied in full-scale systems. However, conventional multizone systems can undergo to structural limitations due to the necessity of over-aeration to prevent membrane fouling and the necessity of satisfying a fixed recycling ratio [6,7], while dynamic systems can be more flexible and easily managed when automatic controls are introduced to manage the process. These can be implemented in sequencing batch reactors [8,9] or in continuously fed reactors intermittently aerated [10,11]. At present, a number of studies deal with the possibility to intermittently aerate the activated sludge in MBRs and most of them propose a setpoint-based control strategy [12–14]. However, most of these results, although excellent, are obtained in lab-scale experiments and treating synthetic wastewaters applying control algorithms based on fix set points: this is a static strategy and cannot be considered for the treatment of real wastewaters, for which a dynamic control is more appreciable. This is the case of auto-controlled alternated processes.

Alternating processes, where intermittent aeration is automatically controlled on the basis of on-line signals, are reported to be a viable and energy saving method and have been successfully adopted since the early nineties in conventional WWTPs [15–17]. The on-line control automation of the intermittent aeration can optimize the flexibility of alternate MBRs and allowing also reliable applications in small plants with very fluctuating inloadings. Very successful application of intermittent aeration automatically controlled and membrane bioreactor has been proposed by Veolia Water with the Biosep® process [18] that regulates the on/off of the blowers on the basis of the redox signal and both nitrification and denitrification are performed in the same tank where also the submerged hollow fiber membranes are installed. The automatic control of the intermittent aeration of the bioreactor on the basis of on-line dissolved oxygen (DO) and redox potential (ORP) has been proposed in demonstration and full application of the alternate cycles process applied to a membrane bioreactor (AC-MBR) [19,20]. This process was demonstrated to be very effective for carbon and nitrogen removal and to be applicable for upgrading of existing plants allowing for the increase of the plant treatment capacity and also for the reduction of the power requirements, meeting, therefore, the recent policies regarding the energy best use [21].

This paper explores the potential of the AC-MBR process for the treatment of municipal wastewater on the basis of two long-term experiences coming from a demonstration and a full-scale plant. The combined discussion of the results allowed to define the performances of the alternated cycles process as well as the industrial economics for the process.

2. Materials and methods

2.1. Demonstration plant

The demonstration plant (Fig. 1) can treat up to 50 m^3/d and is located at the experimental hall at Treviso WWTP (north-east of Italy). The feeding wastewater is continuously taken after the headworks of the full scale plant. After the initial pre-treatments, the flow passes through a further fine screening (openings 1 mm) to protect the submerged membranes from possible trash and hair. An accumulation tank assures a continuous feeding to the plant and allows for the possible mixing with additional influent streams (external carbon sources and/or solutions of nitrogen and phosphorus). The bioreactor is divided into four sectors: an anoxic selector where high F/M ratio favours the growth of floc-forming bacteria to prevent foaming phenomena; two completely stirred tank reactors (AC-CSTR I and AC-CSTR II) equipped with DO and ORP sensors where the alternate cycles are performed; finally the aerated UF section which is equipped with submerged hollow-fibres membranes (ZeeWeed®500c, total membrane area 69.9 m^2).

2.2. Full scale plant

The Viareggio full-scale MBR arises from the upgrading of the existing municipal WWTP, whose original construction is dated back to the 1970s. At the moment the AC-MBR line operates at the side of the pre-existing conventional plant. Wastewater (up to 6,000 m^3/d) is treated in the membrane plant for irrigation reuse purposes, while the rest of the inflow (up to 15,000 m^3/d) is diverted to the old conventional plant. The AC bioreactor has been obtained retrofitting a previous longitudinal primary clarifier and achieving the complete recovery of the existing structures. This tank has been coupled with the ultrafiltration membrane section (submerged hollow-fibres – ZeeWeed® 500d – membrane area 12,130 m^2) so to obtain the AC-MBR process. The plant retrofitting also included the installation of adequate pre-treatments essential to the stable, long-term operation of MBR. Moreover, also an off-line equalization basin was built to feed the AC-MBR with stable flowrate.

2.3. Monitoring plan and nitrogen mass balance

Both the reactors were monitored considering the concentrations of total solids, COD, soluble COD (sCOD), nitrogen and phosphorous forms (NH_4-N, NO_2-N, NO_3-N, TKN, Total P, PO_4-P) in both influent and effluent streams. Then also the MLSS and MLVSS were determined. Chemico-physical parameters were determined according to the *Standard Methods*, analysing composite samples automatically collected over 24 h.

Nitrogen mass balances to find out the effective performance for nitrogen removal were determined according to Battistoni et al. [22].

2.4. Process control strategy

According to the AC automatic control algorithm [17,23], the aeration of the bioreactor is automatically controlled through a strategy based on the control of bending points in on-line profiles of dissolved oxygen (DO) and oxidation reduction potential (ORP). Aeration is switched off (and submerged mixers are switched on) when the ammonia break point is detected, and is switched on when the nitrate flex is detected. In this way, the lengths of the aerobic and anoxic phases are controlled to be just sufficient for complete nitrification and denitrification, respectively. However, the bending points are not always easy to identify. Ammonia break-point on the ORP curve appears only when the DO is subject to a sharp rise from a low level to a significantly higher one at the end of nitrification.

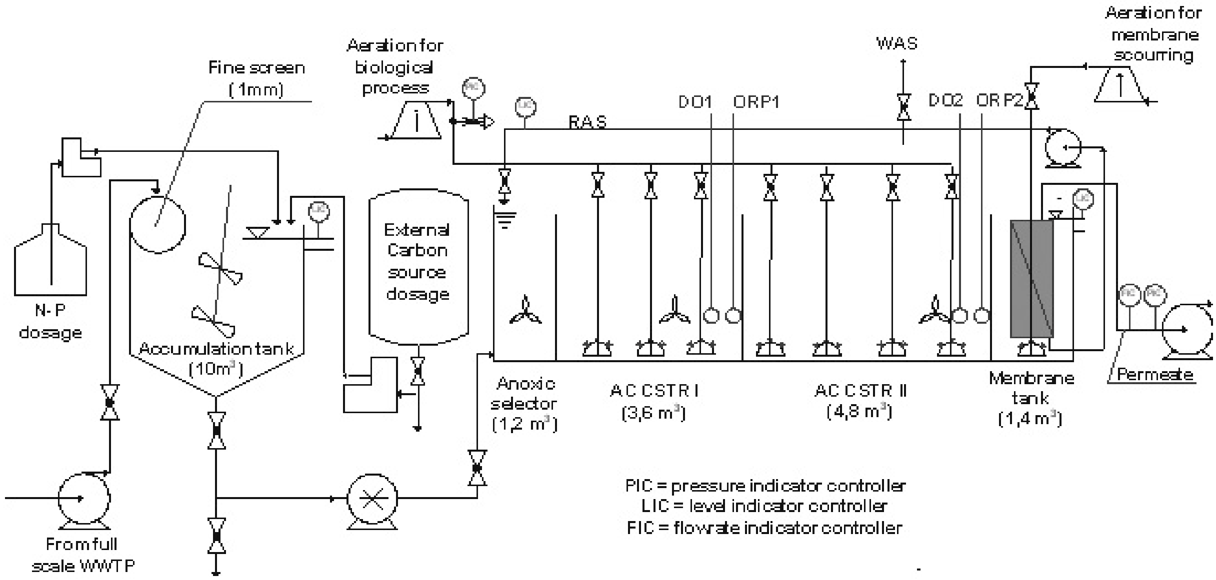

Fig. 1. Schematic representation of the demonstration installation – Treviso.

Similar difficulties may also be found with DO bending points [24]. Furthermore, Paul et al. [25] demonstrated that bending points are not identifiable under particular conditions like over-aeration, under or over-loading, which can be almost common for real wastewater treatment system, especially for small treatment capacities. Finally, with a bending point based strategy, nitrification and denitrification come to their ends in the aerobic and anoxic phase, respectively. This is not necessarily an optimal strategy. For an intermittently aerated continuous system, high effluent ammonia and nitrate peaks may appear alternatively, resulting in high effluent nitrogen concentration, when the plant is over loaded with nitrogen. Therefore, the complete control algorithm has been provided with secondary branches which are based on setpoints of the time lengths of the aerobic and anoxic phases and of the absolute values of DO or ORP. These secondary branches represent a secondary safety level of the automatic control and are initially set by simulations with the activated sludge model, then they are adjusted after the initial trials operations of the plant so to reach the assessment which best fits the particular case study. Table 1 shows the setpoints which could be set to complete the automatic control of the process.

Table 1
Set-points included in the secondary branches of the algorithm

	Aerobic phase		Anoxic phase	
	Max	Min	Max	Min
DO	X			
ORP	X			X
Time-length	X	X	X	X

3. Results and discussion

3.1. Characteristics of the feeding sewage

Alternating systems primarily based on the bending point detection are driven from the rate

Table 2
Characteristics of raw wastewater at Treviso WWTP

pH	Alkalinity mgCaCO$_3$/L	TSS mg/L	COD mg/L	rbCOD mg/L	NH4-N mg/L	TKN mg/L	NO3-N mg/L	PO4-P mg/L	TP mg/L
7.4–7.8	230–350	80–100	90–160	17–21	11–15	20–23	0 .4–1.0	0.7–12	1.8–2.2

Table 3
Characteristics of wastewater used for the experimentation at Treviso WWTP

	Modification	TSS mg/L	COD mg/L	sCOD mg/L	TN mg/L	NH4-N mg/L	TP mg/L
Run1	None	90±88	112±53	33±16	21.9±6.9	11.7±4.5	1.7±0.7
Run2	None	89±73	93±54	23±25	23.9±5.9	15.2±3.0	1.9±0.6
Run3	Acetate	94±9	217±73	108±53	23.5±4.0	16.2±2.5	2.8±0.8
Run4	External C	286±107	285±217	58±48	32.3±15.2	15.4±10.7	4.8±1.4
Run5	External C, N, P	190±82	169±47	32±14	45.1±6.0	37.7±4.6	10.3±2.0
Run6	N, P	271±187	291±154	52±20	52.2±9.2	23.4±3.5	9.0±2.8
Run7	External C, N, P	208±156	245±116	51±18	39.5±20.6	16.9±9.2	6.1±2.8
Run8	N, P	155±49	149±40	42±24	66.0±5.1	56.8±3.8	8.6±1.4
Run9	External C, N, P	582±72	413±138	37±21	78.1±17.1	53.5±11.6	14.8±2.2

limiting steps, which can be either biological nitrifications or denitrification. The biokinetics of these reactions are dependent on a number of saturation terms. With particular concern to the denitrification, the abundance and the degree of biodegradability of the carbon source plays a fundamental role. In the two AC-MBR plants presented in this paper, the influent sewages had very different characteristics, so to make almost generalizable and practicable the final empiric remarks.

The demonstration reactor treated almost domestic and severely diluted wastewater (Table 2). Along the experimentations, the characteristics of the raw wastewater were also modified by adding nutrients and /or external carbon sources (Table 3).

The wastewater treated in Viareggio WWTP is a medium-high strength municipal wastewater, particularly rich in rbCOD probably discharged also by some agro-industrial factories present in the catchments area (Table 4). As for the fluctuations of the loading, it changes quite considerably considering the summer or winter period, as Viareggio is a famous beach on the Tirreno Sea.

Dealing with intermittent processes which control is based on the nitrogen forms in the reactor, it is important to focus on the nitrogen loading rates (NLRs) and the C:N ratios (Table 5) because these parameters are fundamental in driving the whole alternation of the phases.

Particular attention should be paid to the NLR since this parameter can well describe the potential of the AC-MBR to upgrade existing treatment municipal treatment systems and achieve the reuse purpose. Typical NLRs usually adopted in Italy to design municipal WWTPs were in the range 0.06–0.08 kgN $m^{-3}d^{-1}$, but once in operation, these values were found to decrease to 0.04–0.05 kgN $m^{-3}d^{-1}$ for numerous real small wastewater treatment systems. Therefore, it is clear the potential of the AC-MBR process to

Table 4
Characteristics of the wastewater — Viareggio

	High loading (summer)	Low loading (winter)
	Average ±SD average	Average ±SD average
COD (mg L^{-1})	657 ± 105	604 ± 97
NH4-N (mg L^{-1})	39 ± 4	34 ± 7
TN (mg L^{-1})	64 ± 7	47 ± 4
TP (mg L^{-1})	7.2 ± 0.7	5.0 ± 1.1
TSS (mg L^{-1})	264 ± 77	255 ± 49
COD/TN	12.4 ± 2.9	13.1 ± 2.6

Table 5
Nitrogen loading rates and C/N ratio to the demonstration and full scale MBRs

	Demonstration	Full scale
C:N[a]	3–8	8–15
NLR (kgN m^{-3}_{reac} d^{-1})	0.05–0.25	0.08–0.16

[a]Mass ratio.

improve the effluent quality up to meet the reuse standard, and to increase, at the same time, the treatment capacity of the existing systems.

3.2. Operating parameters

The applied operating parameters for MBRs treating municipal wastewaters is one of the key issues to optimize the removal performances and energy utilization and also to extend the membrane life. The management of the MBRs is not related to sedimentation properties of the activated sludge, so very high MLSS content (up to 30 g L^{-1}) and sludge ages can be applied. However, high solid contents in the mixed liquor were found to be the main parameter that involves the decrease of the oxygen transfer capability in membrane bioreactors [26]. In particular, both the k_La_{20} and the α-factor decreased at higher MLSS concentrations, involving a low aeration efficiency and increasing operating costs [27]. Moreover, MLSS is often considered at a first glance, as the main fouling parameter and, although the findings about this argument are sometimes controversial [2], high concentrations of MLSS are often reported to reduce the expectations for membrane life. To sum up, high MLSS seem to increase both operating costs and the expenses for membrane replacement. On the other hand, some studies reported the possible decrease of the excess sludge production thanks to the reduced biomass yields, that might lead to decrease of costs for sludge final disposal [5,28]. However, these results are controversial and there is a lack of data coming from real applications which can reliably confirm this effect on the biomass metabolism. Furthermore, in municipal plants provided with anaerobic digesters, the waste activated sludge is used to produce biogas and, often, to be co-digested with other organic substrates. Therefore, in these systems the excess sludge is not of major concern for the overall economic balance [5].

According to this evidence, the different operated SRTs for both the demonstration and the full-scale bioreactors had MLSS concentrations under 10 g L^{-1}. In particular, the achievement of complete nitrification of ammonia addressed the choices, summarized in Table 6. MLSS concentration was maintained as low as necessary for the complete ammonia nitrification. This operating strategy makes clear the reason why in high loading periods a lower biomass concentration was held in the bioreactor (see Table 6 regarding the full scale experiments).

3.3. Nitrogen removal: efficiencies and maximal treatment capacity of the process

The behaviour of the AC-MBR process for nitrogen removal was slightly different in the two systems analysed; in fact, nitrification and denitrification were the driving steps respectively

Table 6
Comparison of operational parameters at pilot and full scale

	T	HRT	SRT	$MLSS_{ACtank}$	MLVSS/MLSS	Total recycle ratio
	°C	h	d	kg/m^3	%	%
Pilot scale	11–23	8–11	22–48	5–9	62–70	1.5–2
Full scale – LL	13.8–24.3	9–11	13–15	8	68–77	2
Full scale – HL	26.1–26.5	9–11	14–21	6	62–67	2

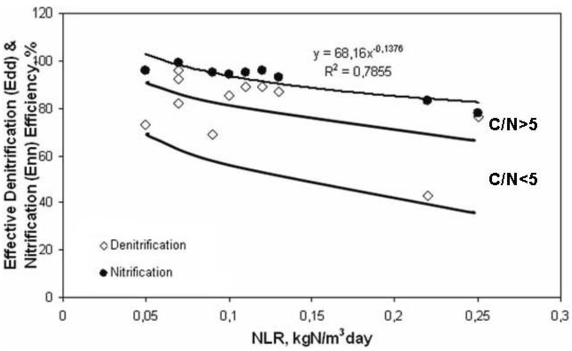

Fig. 3. Nitrification and denitrification effective efficiencies in the AC-MBR plants.

for the full-scale and demonstration AC-MBRs. The effective nitrification and denitrification efficiencies were calculated according to the nitrogen mass balance [21] which takes properly into account the nitrogen removed for biomass assimilation. Therefore in Fig. 3, which combines the efficiencies of both the AC-MBR plants considered in this paper, E_{nn} is the nitrified over the nitrifiable nitrogen, while E_{dd} is the denitrified nitrogen over the sum of the nitrified nitrogen and incoming nitrates.

According to Fig. 3, the nitrification in the alternating MBRs was always satisfactory, although for NLRs higher than 0.16–0.18 kgN/m^{3}d the system was no longer able to meet the ammonia limit for irrigation reuse (2 mgN/L). It is important to point out that the nitrification capacity was not significantly influenced from the sludge age within the operating temperatures: no significant benefits were observed passing from 15 to 48 days. As far as the nitrate denitrification, this process was always optimized by the system according to the available carbon source. A clear example is given under NLR at 0.25 kgN m^{-3}d^{-1} when, notwithstanding the incomplete ammonia nitrification, the high denitrification efficiency optimized the removal of total nitrogen as far as possible. As better discussed later, this behaviour impacts positively also on the aeration requirements and the following energy consumptions.

A possible indicator of the maximal treatment capacity for a dynamic system, such as the AC-MBR, can be the loss of flexibility of the process. This is, in other words, the border line beyond which the alternation of the phases is no longer adjusted adequately to the influent sewage. As for the C:N ratio, the results from both the plants are well interpolated by the curve of Fig. 4.

Fig. 4 shows as the system lost its flexibility for C:N lower than 5–6 where loss of flexibility means the shift from a dynamic system (which is able to adjust the anoxic/oxic durations according to the influent C and N loadings) to a static system (which, practically, operates at fixed anoxic/oxic durations, in spite of the loading fluctuations in the influent wastewater). In fact, a plateau is reached under this value of C:N, that is consistent also with the efficiencies shown in Fig. 3. Furthermore, it should be observed that the curve of Fig. 4 results from the interpolation of different AC-MBR plants fed with substantially different types of carbon sources. Therefore, these results may assume general and practical interest. In other words, as soon as the influent C:N drops

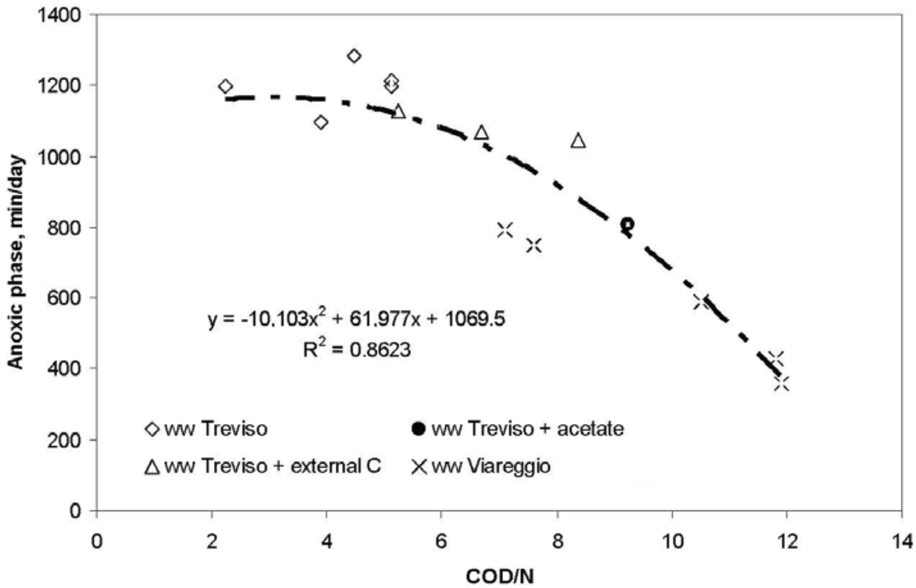

Fig. 4. C/N ratio and anoxic times in the AC-MBR plants.

under 5–6, the system becomes static, unable to reach complete denitrifications and regulated on the basis of the set-points. As far as concern the use of the carbon source, the system was able to reach unexpected high efficiencies of nitrates denitrification notwithstanding the rather low amounts of easily biodegradable COD. Such a phenomenon could be related to the particular best use of the slowly biodegradable COD by the biomass in MBRs. This behaviour had been already observed for a MBR operating post-denitrification which, unexpectedly, showed high denitrification rates [29]. As a matter of fact, this good propensity for nitrates denitrification has been found also in our intermittent MBRs. This fact seems to indicate the ability of the MBRs biomass of making a more effective use of the carbon source, probably with particular relation to the slowly biodegradable COD [29].

As for the loss of flexibility of the AC-MBR system in terms of maximum NLRs, the influent to the full-scale plant has a carbon source sufficient to suppose the aerobic–anoxic phases influenced only by the influent nitrogen. So

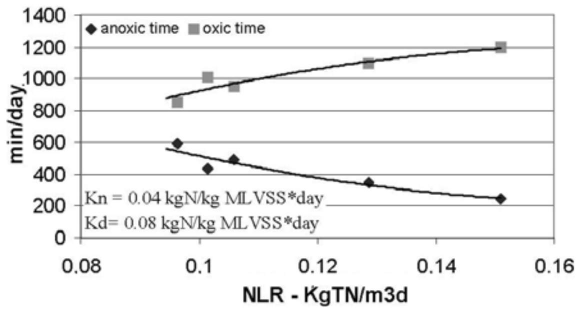

Fig. 5. Durations of anoxic and oxic times.

Fig. 5 shows the durations of the aerobic and anoxic phases with respect to the NLRs and is used to identify the indicator of maximal capacity.

Fig. 5 makes clear that the AC-MBR system lost its flexibility for NLRs higher than 0.16–0.18 kgN m^{-3} h^{-1}. From the practical standpoint, the results just mentioned let suppose that the application of AC-MBR process for up-grading of existing plants can drastically increase the nitrogen treatment capacity and also allow to meet the nitrogen standard for the reuse of the treated effluent.

3.4. Key indicators for performances evaluation

3.4.1. Nitrogen removal

Some simple key performance indicators are suggested by Olsson et al. [24] to evaluate both nitrification efficiency and nitrogen removal. For the nitrification efficiency one should consider that the aeration for the aerobic biochemical reactions is one of the main energy user, and that the more the organic carbon is degraded anoxically, the less energy is consumed by the biological process. A simple key indicator of the energy use performances is the amount of nitrogen biologically removed per kWh. In the particular case of AC-MBR systems, it must be taken into account that the final membrane tank is also an effective aerobic bioreactor where both the ammonia nitrification and the phosphorus luxury uptake can be performed. Therefore, Table 7 reports the key indicator "energy use" with reference to both the only AC reactor and the whole AC-MBR system.

Basically, from Table 7 it is clear that the alternating process was able to optimize the energy consumptions. In fact, Olsson [24], reporting the results of a survey on a number of Swedish conventional WWTPs, pointed out the energy consumption for ammonia nitrification 79 and 173 gNH_4-N per kWh installed for the overall system and for the only aeration, respectively. On the other hand, the performances referred to the overall energy installed for the aeration (AC bioreactor and UF membrane scouring) were similar to the values reported for conventional activated sludge systems.

As for the total nitrogen removal, since the available organic matter and the biological volume largely limit the performances, the key indicators consider these aspects. The use of the biological volume has been indirectly illustrated before, discussing the limiting NLR. On the other hand, Fig. 6 shows the removed total nitrogen per available amount of total organic matter.

The system was able to remove 0.0966 kg of total nitrogen per kg of total influent COD that is in agreement with the data reported by Olsson et al. [24]. However, in the demonstration AC-MBR plant the best use of the carbon source was sometimes not achieved because of over-aeration phenomena during the aerobic phases. Therefore, Fig. 6 can be taken as indicator of the minimal performance for the use of the carbon source.

3.4.2. Viability and reliability of the control strategy for municipal MBRs

So far, the control strategy for the intermittent aeration seemed reliable and effective. However, although the removal performances gave almost objective and unquestionable information about the efficiency of the process, the statistical analysis of the cycles can give information on the real detection of the bending points (optimal conditions) or the intervention of the setpoint branches of the control algorithm. The results from the combined analysis are the key indicator for the reliability of the control strategy.

Table 8 shows the output from the elaboration of more than 5,000 cycles over the whole experimental period. In this table the optimal condition,

Table 7
Key performance indicators for nitrogen removal

	$gTN_{removed}$ per kWh_{AC}	$gTN_{removed}$ per $kWh_{AC\text{-}MBR}$	$gTN_{removed}$ per $kWh_{aerationAC}$	$gTN_{removed}$ per $kWh_{aerationAC\text{-}MBR}$
Low loading	284	85	323	131
High loading	315	109	333	158

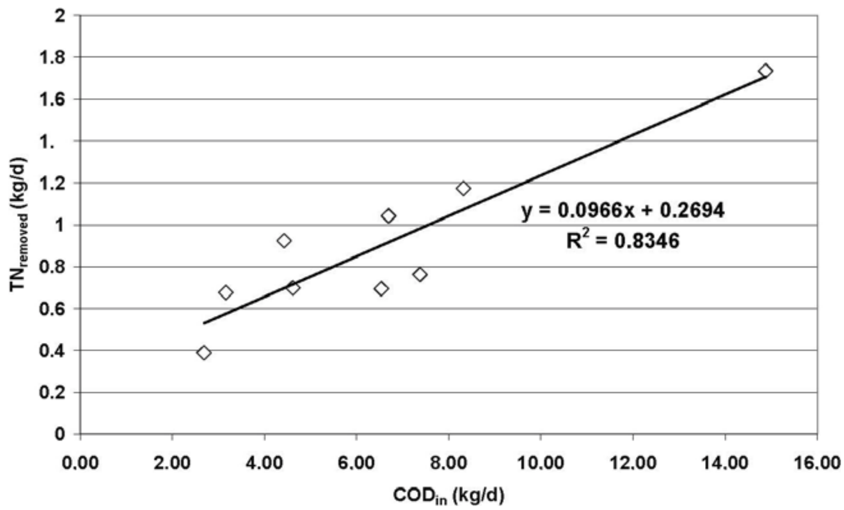

Fig. 6. Performance key indicator: use of the carbon source.

Table 8
End -reason during the demonstration experience (%)

	Aerobic phase			Anoxic phase		
	α	β	γ	α	β	γ
Run1	93	7	0	74	0	0
Run2	67	1	32	96	4	0
Run3	98	2	0	100	0	0
Run4	73	0	27	100	0	0
Run5	75	4	19	72	28	0
Run6	98	2	0	80	23	3
Run7	94	4	2	86	7	7
Run8	53	33	14	25	75	0
Run9	59	41	1	58	42	0

that is the detection of the bending point, is called α, while β and γ represents respectively the cases when the time and the DO-ORP set points were exceeded and the secondary branches of the control algorithm were used.

From the data reported one can observe as the detection of the ammonia break point was rather common, so a complete ammonia nitrification was usually observed. On the other hand, the non-optimal conditions are in agreement with influent loadings: in runs 4 and 5 over-aeration often occurred in the nights when the aeration demand was much lower than the supply; in runs 6 and 7 the influent oxidizable nitrogen fits the air supply; in runs 8 and 9 a nitrogen over-loading involve the detection of the ammonia break points only for some 50% of the events, while the aeration is stopped for the achievement of the set maximal time-length. With specific reference to the anoxic phases, as it was expected, the optimal

Table 9
Number and durations of the cycles — Viareggio

	NLR	COD/N	Cycles/d	Aerobic phase		Anoxic phase	
	kgN/m^3d			d/d	min	d/d	min
Low loading	0.1	13.1	14	0.59	61	0.41	42
High loading	0.13	12.4	12	0.78	97	0.22	28

Table 10
Ending of the cycles (%) — Viareggio

	Aerobic phase			Anoxic phase		
	α	β	γ	α	β	γ
Low loading	73	19	8	75	7	18
High loading	70	20	10	78	1	21

conditions depended mainly on the C/N ratio. It is important to point out that the set point on the aerobic phase allowed to stem the waste of biodegradable COD linked to over-aeration phenomena. As a result, in run 4 a COD/N equal to 8.4 involved over-aeration for 27% of the events, but 100% of nitrates break points were found out in the anoxic phases. Even under nitrogen over-loadings (runs 8 and 9) the nitrates break-points were detected with lower but satisfactory frequency. This means that such a dynamic alternate system is usually able to optimize its own performances thanks to its flexibility, but it is fundamental to impose the right setpoints that mark the boundary lines of the process. So, the wastewater characteristics are confirmed to be the main driving force for the process behaviour.

The validation through the cycles analysis was carried out also in the full scale AC-MBR. Tables 9 and 10 report respectively the durations of the phases, expressed as overall averages, and the *end-reasons* for the intermittent aeration control.

The nitrogen removal performances are consistent with the high percentages of detected bending points for both the aerobic and anoxic phases. Better performances of the control device were found for the anoxic phases. As a matter of fact, the end of the anoxic phase was optimal for almost all the cycles. In fact, when the nitrate knees were not detected, the aeration was switched on for the minimum value of ORP ("γ" cases in Table 10) that indicates complete and very fast denitrification up to anaerobic conditions. On the other hand, the ammonia break-points were identified for around 70%, while over-aeration occurred for around 10% ("γ" cases in Table 10), usually during night times, and the time setpoints control was used for around 20% ("β" cases in Table 9), usually late in the mornings.

4. Conclusions

The results from the long-term operation of a demonstration and full-scale MBRs intermittently aerated have been presented. The technology was proposed for the treatment and reuse of municipal wastewater and the key performance indicators proved its reliability.

The scale of the experimentations allows to generalize the results, so to outline the "know-how" for this kind of automatically controlled system applied to membrane bioreactors.

The main remarks of the study were the following:

1. The system was able to adjust the alternation and the length of anoxic and aerobic phases, so to optimize the aeration for the biological process for NLRs in the range 0.05–0.18 kgN m^{-3} d^{-1} and C:N mass ratios greater than 5–6. In practice, these values mark the border lines beyond which alternating processes are no more flexible with respect to the influent loading fluctuations. However, considering the actual loading conditions for the major part of the Italian municipal wastewater treatment plants, the AC-MBR can be adopted both for new systems and also to upgrade existing ones, increasing the nitrogen treatment capacity and meeting with the reuse standards.

2. The use of the available carbon source, with concern to the total nitrogen removal, was as low as 0.1 kg of total nitrogen removed per kg of total influent COD. However this value is affected by phenomena of over-aeration of the activated sludge and can reasonably be considered as a minimal performance for such an alternating membrane bioreactor.

3. The system was able to optimize the removal of total nitrogen achieving while at the same time minimizing the power requirements, according to the best energy saving practices.

4. The control strategy was validated at different scales so to consider the technology ready for the widespread, full-scale application.

Acknowledgements

This work was realized thanks to the funding of the Italian Ministry of University and Research, within the projects PRIN2003 and PRIN2005. The Treviso municipality is also kindly acknowledged for hosting the experimental facilities in the municipal wastewater treatment plant and stimulating the research regarding environment-related issues.

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