# EVALUATION OF BIOMASS ACTIVITY IN MEMBRANE BIOREACTORS BY MEANS OF RESPIROMETRIC TECHNIQUES

D. DI TRAPANI*, G. MANNINA*

* *Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali (DICAM) Scuola Politecnica, Università' di Palermo, Palermo, Italy*

**Keywords:** MBR; respirometry; mathematical modeling; biokinetic coefficients; MB-MBR

**Abstract.** *The paper reports the main results of a respirometric experimental survey carried out on several membrane bioreactor pilot plants, characterized by different pilot plant layouts as well as operational conditions. The main aim was to assess the influence of specific conditions on biokinetic/stoichiometric parameters. In particular, the respirometric tests were specifically aimed at investigating the activity of both heterotrophic and autotrophic bacterial species. The achieved results showed that the plant configuration and the features of the feeding wastewater and operational conditions determine significant variation of the kinetic coefficients. The respirometric analysis was confirmed to be a simple and effective tool for the evaluation of the actual biomass kinetic parameters, to be used in mathematical models for the design phase as well as for monitoring the biomass viability during plant operations.*

## 1. Introduction

Nowadays, the higher regulatory pressure derived by an increased sensitivity towards environmental protection has driven the scientific and technical communities to the recurrence of new technologies for wastewater treatment. Among these new technologies, membrane bioreactors (MBRs) in the last years are being even more employed for wastewater treatment (Judd and Judd, 2010). The increasing development of MBRs is undoubtedly related to the several advantages characterizing this technology. Indeed, MBRs feature high effluent quality, significant decrease of the reactor volumes, high sludge retention times (SRTs) which enhance the development of a nitrifying community able to sustain complete nitrification, and low sludge production rates compared with conventional activated sludge (CAS) systems (Smith et al., 2003; Judd 2006). However, depending on the specific conditions (including wastewater characteristics, plant configuration, operational conditions, etc.) a modification in biomass kinetics as well as in sludge characteristics may arise and this situation is of paramount importance, since microbial community characteristics might have a primary role in membrane fouling, which still represents one of the major drawbacks for MBRs (Gao et al., 2013; Guo et al., 2012; Meng et al., 2009). Consequently, the MBR operational costs (deriving from high energy consumption or chemicals required for membrane cleaning) can hamper an easily world-wide application (Mannina and

Cosenza, 2013). Four groups of factors mainly affect membrane fouling: membrane materials, mixed liquor characteristics, feed water characteristics and operating conditions (i.e., sludge retention time (SRT), hydraulic retention time (HRT) and food to microorganism ratio (F/M)) (Le-Clech et al., 2006; Meng et al., 2009). In particular, specific stress conditions on the biomass can promote a modification in the biokinetic parameters affecting at the same time the membrane fouling tendency, mainly because of high extracellular polymeric substance (EPS) production, which promotes the formation of a dense and compact cake layer. In this context, respirometric techniques (Munz et al., 2008; Capodici et al., 2016) may represent a useful tool for the characterization of the biokinetic behavior of microorganisms in a MBR system and for the achievement of biokinetic parameters to be used in mathematical models during the design phase. Respirometry can be also used to monitor the biomass active fraction (Majewsky et al., 2011; Ramdani et al., 2012) or viability (Di Trapani et al., 2011). Indeed, oxygen uptake rate (OUR) is widely recognized as an important parameter to monitor the biomass viability (Spanjers et al., 1996). It is worth noting that respirometry, although a quite "simple" and "conventional" analytical procedure, allows the comparison of the "biokinetic features" of different bacterial cultures, collected by different plants, based on an identical protocol of analysis (e.g., same range of oxygen variation, biodegradable synthetic wastewater, and temperature). Nevertheless, the biokinetic values evaluated with this technique are not always directly comparable with the values obtained by model calibration techniques adopted for a specific plant (Mannina et al., 2011). Conversely, the respirometric analysis allows the comparison of homogeneous biokinetic conditions of the biomasses grown in different biological reactors (Di Trapani et al., 2011).

Bearing in mind these considerations, the paper presents the main results of a respirometric survey for the evaluation of heterotrophic and autotrophic kinetic/stoichiometric parameters in several MBR pilot plants, characterized by different plant configuration as well as different influent features and operational conditions. In particular, the following pilot plants were investigated: a sequencing batch MBR (SB-MBR) subjected to salinity increase (Mannina et al., 2016a); a MBR system in a pre-denitrification scheme for the treatment of saline wastewater contaminated by hydrocarbons (Mannina et al., 2016b); a MBR pilot plant coupled to a University of Cape Town configuration (UCT-MBR) aimed at analyzing the influence of the inlet C/N (Mannina et al., 2016c); a hybrid moving bed biofilm membrane bioreactor in a UCT configuration (UCT-MBMBR) pilot plant for carbon and nutrient removal.

## 2. Materials and Methods

### *2.1. MBR pilot plants description*

In this study, four MBR pilot plants were monitored for the evaluation of the biokinetic/stoichiometric parameters. The basic features of the pilot plants are listed in Table 1. The investigated pilot plants were chosen in order to provide a wide range of plant configuration, influent quality and operational conditions, thus elucidating the factors that might influence the kinetic behavior of MBR processes. According to authors, the selected MBR systems might be representative for different MBR applications in full scale plants. Figure 1 reports a schematic layout of the investigated pilot plants.

Briefly, the pilot plant N°1, named SB-MBR, was designed according to a pre-denitrification scheme and

consisted of two reactors in series, one anoxic (volume 45 L) and one aerobic (volume 224 L) and a MBR compartment (50 L). Furthermore, an oxygen depletion reactor (ODR) was installed between the MBR compartment and the anoxic reactor. The experiment was divided into six Phases, with each characterized by a different salt concentration in the feeding wastewater. In detail, the salt concentration was gradually increased from 0 to 10 g NaCl L-1 (Phase I: no salt addition, Phase II: 2 g NaCl L-1, Phase III: 4 g NaCl L-1, Phase IV: 6 g NaCl L-1, Phase V: 8 g NaCl L-1 and Phase VI: 10 g NaCl L-1). The NaCl dosing was increased 2 g NaCl L-1 per week.

**Table 1.** *Description of the monitored MBR pilot plants*

| No. Pilot plant Name | Configuration | Influent Flowrate Q [L $d^{-1}$] | Influent COD and $NH_4$-N [mg $L^{-1}$] | SRT [d] | Membrane typology | Brief process description |
|---|---|---|---|---|---|---|
| 1. SB-MBR | Sequencing batch operation | 320 | 240<br>30 | Indefinite | Ultrafiltration hollow fiber GE Zenon ZW10® | Effect of a gradual salinity increase (0-10 gNaCl/L) in the short term. Experiment divided into six Phases (Mannina et al., 2016a) |
| 2. MBR | MBR in a pre-denitrification scheme | 480 | 350<br>50 | Indefinite | Ultrafiltration hollow fiber GE Zenon ZW10® | Joint effect of salinity (10-20 gNaCl/L) and hydrocarbons (20 mg TPH $L^{-1}$) in the short term (Mannina et al., 2016b) |
| 3. UCT-MBR | MBR coupled to UCT configuration for carbon and nutrient removal | 480 | 411-502<br>52.6-99.2 | Indefinite | Ultrafiltration hollow fiber PURON® | C/N ratio effect in a BNR process integrated with a membrane module for solid/liquid separation phase (Mannina et al., 2016c) |
| 4. UCT-MBMBR | Hybrid moving bed biofilm membrane bioreactor coupled to UCT configuration for carbon and nutrients removal | 480 | 607<br>65 | Indefinite<br>30<br>15 | Ultrafiltration hollow fiber PURON® | SRT effect on the performance of a UCT-MBMBR pilot plant, evaluating the biokinetic activity of the bacterial species |

Pilot plant N° 2 consisted of a feeding tank (volume of 320 L) in which real domestic wastewater was stored, and two reactors in series, one anoxic (volume 45 L) and one aerobic (volume 224 L), according to a pre-denitrification scheme. The experimental campaign lasted 90 days and was divided into two phases: (i) acclimation to an increasing feeding salt rate lasting 30 days (Phase I), and (ii) constant feeding salt rate (20 g NaCl $L^{-1}$) and hydrocarbon dosage lasting 60 days (Phase II).

Pilot plant N°3 consisted of an anaerobic (volume 62 L), an anoxic (volume 102 L) and an aerobic (volume 211 L) tanks according to the UCT scheme (Ekama et al., 1983). The solid–liquid separation phase was carried out by means of an ultrafiltration hollow fibre membrane (PURON®). The UCT-MBR pilot plant was fed with municipal wastewater mixed with a synthetic wastewater characterized by Sodium Acetate ($CH_3COONa$), glycerol ($C_3H_8O_3$), dipotassium hydrogen phosphate ($K_2HPO_4$) and ammonium chloride (NH4Cl). the experimental campaign was divided in two phases each characterized by a different C/N value: (i) Phase I, with

a C/N = 10 (duration: 41 days); (ii) Phase II, C/N = 5 (duration: 39 days).

Pilot plant N° 4 consisted of an anaerobic (volume 62 L), an anoxic (volume 102 L) and an aerobic (volume 211 L) tanks according to the UCT scheme (Ekama et al., 1983). The solid-liquid separation phase was carried out by means of an ultrafiltration hollow fibre membrane (PURON®). The anoxic and aerobic compartments were filled with suspended plastic carriers (carriers density = 0.95 g $cm^{-3}$; carriers specific surface = 500 $m^2$ $m^{-3}$), with a 15 and 40% filing ratio, corresponding to a net surface area of 75 and 200 $m^2$ $m^{-3}$ in the anoxic and aerobic reactor, respectively. The experimental campaign was aimed at assessing the influence of mixed liquor SRT on the system performance. The following conditions were investigated: No sludge withdrawals (indefinite SRT) 30 and 15 days SRT, respectively.

For further details on the pilot plants description as well as on the experimental campaigns, the reader is addressed to literature (Mannina et al., 2016a-c).

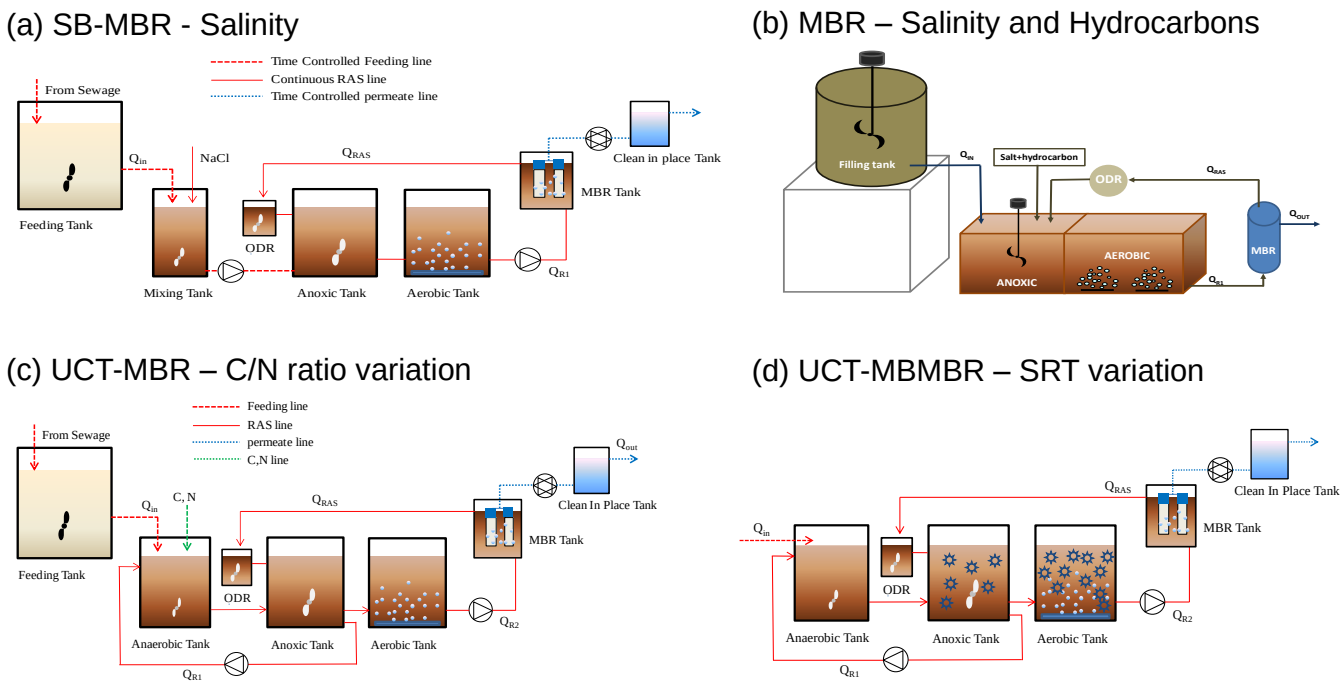


**Figure 1.** *Schematic layout of the investigated MBR pilot plants: SB-MBR (a), MBR fed with salt and hydrocarbons (b), UCT-MBR (c) and UCT-MBMBR (d)*

## *2.2. Description of the respirometric batch tests*

Respirometric batch tests were conducted using a “flowing-gas/static-liquid batch respirometer” (Spanjers et al., 1996). The batch tests were carried out on biomass samples withdrawn from the aerobic compartment of each investigated pilot plant. Referring to suspended biomass, the samples were moved to the respirometer and eventually diluted with permeate, if necessary, in order to obtain a mixed liquor volatile suspended solid (MLVSS) concentration in the range of 2.0–3.0 g VSS $L^{-1}$. This dilution was necessary to make the achieved results comparable, regardless of the corresponding biomass concentration in the pilot plant. Conversely, the batch tests on biofilm were carried out with suspended carriers and permeate, by imposing in the respirometer the same filling fraction of the UCT-MBMBR pilot plant. Before running the batch tests, the biomass samples

were aerated until endogenous conditions were reached, on the basis of the measured OUR values. The samples were maintained at a constant temperature of 20±1°C with a thermostatic cryostat. Mixing was provided by a magnetic stirrer and samples were intermittently aerated by using aeration pumps. For further details on the adopted procedure, the reader is referred to literature (Di Trapani et al., 2011). In the batch tests aimed at assessing the biokinetic parameters of the heterotrophic species, the nitrifying biomass was inhibited by adding 10-15 mg $L^{-1}$ of Allylthiourea (ATU), while the exogenous OUR was enhanced by spiking a readily biodegradable organic substrate (sodium acetate in this case). The substrate biodegradation rate was assumed proportional to the exogenous OUR, according to the following expression:

$$\Delta COD = \frac{\Delta O_2}{1 - f_{cv} \cdot Y_H} \qquad (1)$$

where $f_{cv}$ is the conversion coefficient from COD to VSS, assumed equal to 1.42 mg COD $mg^{-1}$ VSS, while $Y_H$ is the yield coefficient [mg VSS $mg^{-1}$ COD]. The yield coefficient $Y_H$ has been derived from the integral of the exogenous OUR chart, according to the methodology suggested by Vanrolleghem et al. (1999). Furthermore, the maximum heterotrophic growth rate $\mu_{H,max}$ ($d^{-1}$) and the half saturation coefficient $K_S$ (mg COD $L^{-1}$) were evaluated by solving the Monod-type kinetic expression with the finite difference procedure, by fitting the following equation:

$$\frac{\Delta COD}{\Delta t} = \frac{\mu_{H,\max}}{Y_H} \cdot \frac{COD}{(K_S + COD)} \cdot X_H \qquad (2)$$

where COD is the carbonaceous substrate concentration at time t (mg $L^{-1}$), $X_H$ is the biomass active fraction (mgVSS $L^{-1}$), while $\mu_{H,max}$ and KS have been previously defined. The estimation of the endogenous decay coefficient $b_H$ and the heterotrophic active fraction were carried out according to the “single batch test” (Ramdani et al. 2012; Di Trapani et al. 2014). Briefly, the biomass samples were subject to aerobic digestion for several days (at least 5, in the present study) without external substrate addition and the endogenous respiration rate was monitored; $b_H$ was then derived from the slope of the respiration/time linear regression curve.

The estimation of the kinetic parameters for the autotrophic population was carried out with the same procedure. Nevertheless, no inhibiting substance like ATU was added and ammonium chloride ($NH_4Cl$) was spiked to evaluate the biokinetic parameters. During the test, the pH values were constantly monitored to avoid inhibition of the process; the conversion factor between oxygen and ammonium (NOD: nitrogen oxygen demand) is equal to:

$$\Delta NH_4 - N = \frac{\Delta O_2}{4.57} \qquad (3)$$

Figure 2 shows a schematic representation of the adopted respirometric apparatus.

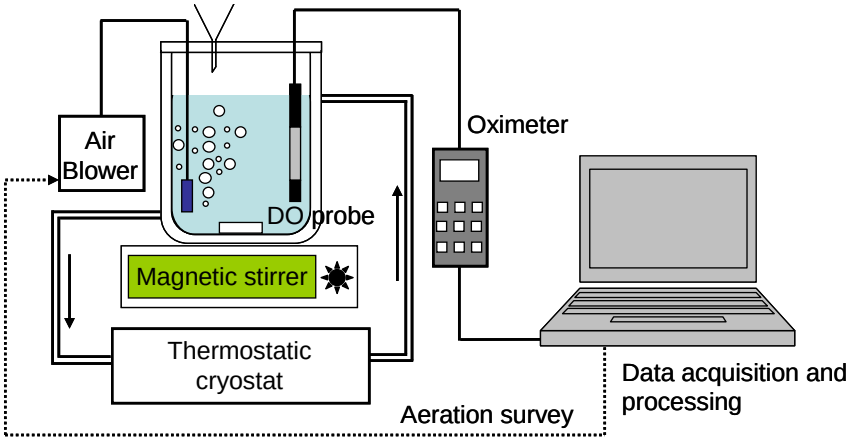


**Figure 2.** *Schematic lay-out of the adopted respirometric station*

## 3. Results and discussion

### *3.1. Characterization of the heterotrophic biomass viability*

The respirogram charts generally featured the typical exogenous and endogenous respiration phases, showing a change in biomass activity depending on the investigated MBR pilot, likely due to the different plant configuration as well as the different operational conditions and influent features that have been investigated. As an example, Figure 3 shows a typical OUR (a) and Monod-type kinetic model (b) profile achieved in the respirometric batch tests, that were used for evaluating the kinetic parameters.

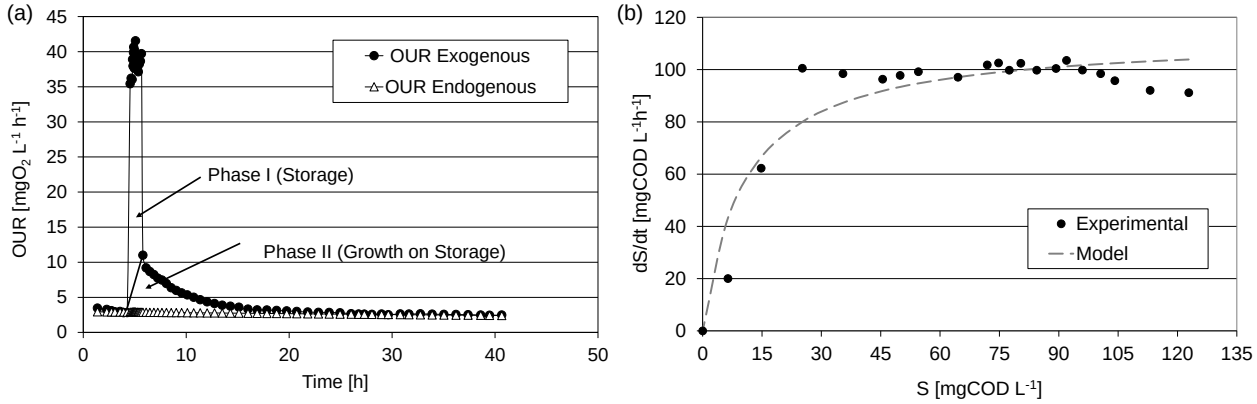


**Figure 3** *Example of OUR profile (a) and Monod-type model curve profile (b) achieved during experiments*

### *3.2. Maximum growth rate ($\mu_{H,max}$), specific respiration rates (SOUR) and decay rate ($b_H$)*

Figure 4 summarizes the average values achieved during the experimental campaigns for the heterotrophic maximum growth rate ($\mu_{H,max}$) (Figure 4a) and the maximum SOUR values (Figure 4b).

From the analysis of Figure 4, it is worth noting that the highest values were observed for the suspended biomass of the UCT-MBMBR pilot plant, whilst the lowest were achieved for the attached biomass in the same

configuration. This result could be related to a sort of “specialization” of the two biomasses, with the suspended one more competitive in the removal of the organic substrate, in good agreement with previous experiences carried out by authors (Di Trapani et al., 2015). Moreover, the C/N ratio was found to be a very sensitive parameter affecting the activity of the heterotrophic suspended biomass. Indeed, both the maximum growth rate and the specific respiration rate of the UCT-MBR plant at C/N = 5 were almost half than that at C/N = 10.

On the other hand, the heterotrophic activity was not significantly affected by salinity and hydrocarbons (SB-MBR Salinity and MBR characterized by salinity and hydrocarbons), with values well in line with what observed when treating domestic wastewater (Mannina et al., 2016a-c).

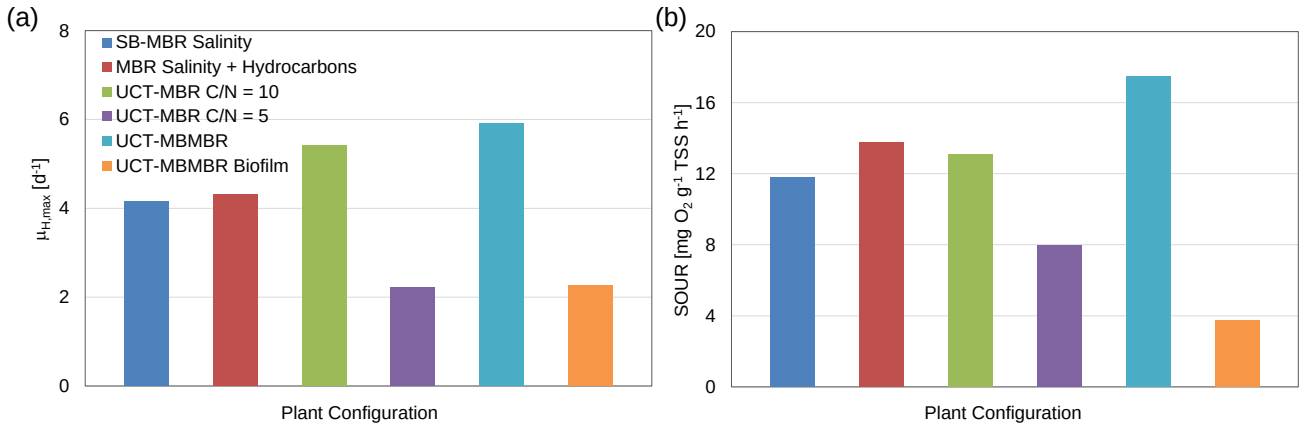


**Figure 4** *Average values of the $\mu_{H,max}$ rates (a) and SOUR (b) achieved throughout experiments*

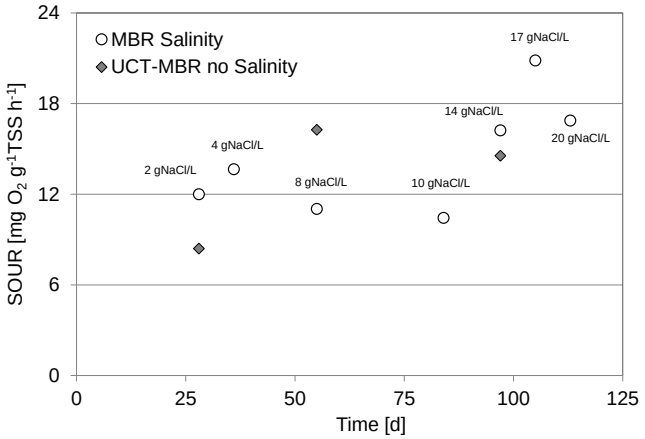


**Figure 5** *Pattern of heterotrophic SOUR respectively for the MBR characterized by a gradual increase of salinity and for the UCT-MBR*

This result is confirmed by the graph reported in the following Figure 5, where the pattern of the SOUR for the SB-MBR and the UCT-MBR is reported. Indeed, from the observation of Figure 5, it is possible to observe that the specific respiration rates were comparable with and without saline wastewater, suggesting that a gradual salinity increase may have exerted a negligible stress on the activity level of the heterotrophic species.

The decay rate $b_H$, which represents a direct indicator of biomass viability, highlighted the differences of the plant configurations and operational features. Figure 6 summarizes the average values of the decay rate values

achieved throughout experiments for the different pilot plants under study. In general, the observed values were in line with typical literature ones (Hauduc et al., 2011).

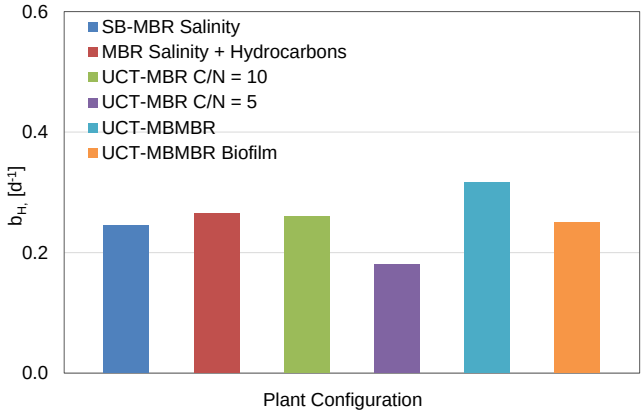


**Figure 6** *Average values of the decay rate bH for the investigated pilot plants*

The results reported in Figure 6 confirmed that the salinity of the influent wastewater did not exert a significant stress effect on the activity of heterotrophic biomass and that the C/N revealed to be more sensitive towards heterotrophic species.

### *3.3. Yield coefficient ($Y_H$) and aerobic storage coefficient ($Y_{STO}$)*

According to the procedure suggested by Vanrolleghem et al. (1999), after sodium acetate addiction, used as readily biodegradable carbonaceous substrate, oxygen is rapidly consumed and immediately after external substrate depletion, the endogenous phase is restored. The achieved $Y_H$ values were in good agreement with those of conventional activated sludge (CAS) systems proposed by Hauduc et al. (2011). Throughout experiments, it was observed a particular shape of the heterotrophic respirogram charts, which suggested the occurrence of the storage phenomenon (Majone et al., 1999; Carta et al., 2011). After sodium acetate addition and the consequent increase of the respiration rate, a tailing of the OUR curve was obtained, highlighting a secondary respiration phase before reaching the original level characterizing the endogenous respiration rate. The storage phenomenon was likely related to the dynamic conditions due to the alternation of aeration/non aeration conditions in the different pilot plants and to the sequencing operation of the SB-MBR plant. These peculiar conditions likely enhanced the development of bacterial groups able to rapidly convert the organic substrate into storage products. The storage yield coefficient ($Y_{STO}$) was evaluated according to the procedure proposed by Karahan-Gül et al. (2002).

### *3.4. Effect of mixed liquor sludge retention time (SRT) variation*

Referring to the effect of sludge retention time (SRT) on the heterotrophic growth rate, Figure 7 shows the results achieved in the UCT-MBMBR pilot plant. As noticeable from Figure 7, the maximum growth rate of the suspended biomass showed a slight decrease in the sub-period characterized by no sludge withdrawals (indefinite SRT), whereas it was observed a significant increase when the SRT was reduced at 30 and 15 days, with a maximum value equal to 7.2 $d^{-1}$ reached at SRT=15. Indeed, when the UCT-MBMBR pilot plant was

operated without sludge withdrawals a sort of suspended biomass “ageing” occurred, while the sludge withdrawals promoted a “renewal” of biomass, thus increasing its growth rate.

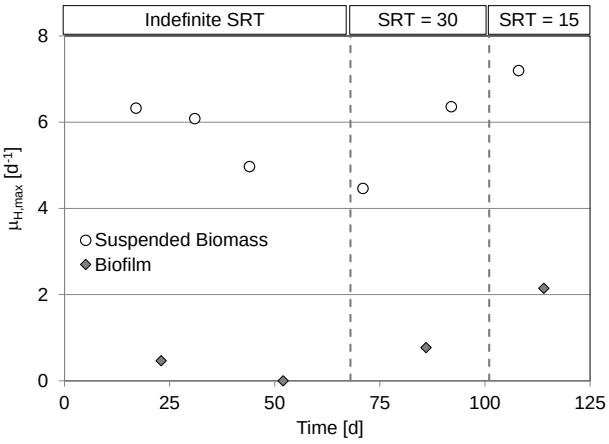


**Figure 7.** *Pattern of heterotrophic maximum growth rate for suspended and attached biomass in the UCT-MBMBR pilot plant.*

Conversely, the maximum growth rate for the biofilm assumed much lower values compared to the suspended biomass. This result can be likely related to the aforementioned specialization of the two biomasses as well as to detachment biofilm phenomena occurring inside the bioreactor.

Finally, Table 2 summarizes the kinetic/stoichiometric parameters achieved in the different experimental campaigns.

**Table 2.** *Summary of the kinetic/stoichiometric parameters measured during experiments*

| **Pilot plant Name** | **Biomass** | **Kinetic/Stoichiometric parameter** | | | | |
|---|---|---|---|---|---|---|
| | | $Y_H$ [mgCOD | $Y_{STO}$ [mgCOD | $\mu_{H,max}$ [$d^{-1}$] | $b_H$ [$d^{-1}$] | SOUR [$mgO_2$ |
| SB-MBR | Suspended | 0.61 (± 0.06) | 0.76 (± 0.02) | 4.15 (± 0.93) | 0.25 (± 0.04) | 11.78 (± 1.41) |
| MBR | Suspended | 0.65 (± 0.09) | 0.79 (± 0.06) | 4.32 (± 1.07) | 0.27 (± 0.25) | 13.77 (± 6.72) |
| UCT-MBR C/N =10 | Suspended | 0.61 (± 0.04) | 0.76 (± 0.03) | 5.41 (± 0.63) | 0.26 (± 0.03) | 13.07 (± 4.13) |
| UCT-MBR C/N =5 | Suspended | 0.62 (± 0.01) | 0.76 (± 0.03) | 2.22 (± 0.65) | 0.18 (± 0.03) | 7.97 (± 1.70) |
| UCT-MBMBR | Suspended | 0.56 (± 0.07) | 0.70 (± 0.05) | 5.90 (± 1.00) | 0.32 (± 0.08) | 17.48 (± 3.97) |
| UCT-MBMBR | Attached | 0.71 (± 0.06) | 0.78 (± 0.01) | 1.13 (± 2.40) | 0.25 (± 0.04) | 3.21 (± 1.71) |

### *3.5. Characterization of the autotrophic activity*

The respirometric batch tests carried out on biomass samples for the evaluation of autotrophic biokinetic behavior highlighted the influence exerted by the specific configuration of the pilot plants as well as the influent wastewater features.

Figure 8 summarizes the average values of the maximum autotrophic growth rate for the investigated pilot plants.

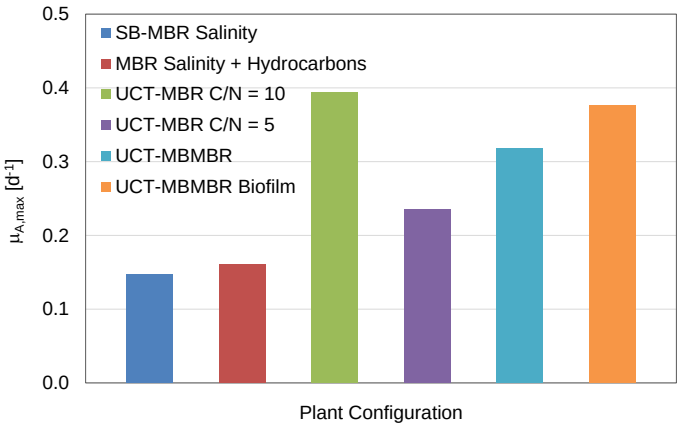


**Figure 8.** *Average values of the $\mu_{A,max}$ for the different pilot plants under study*

As noticeable from Figure 8, in this case the salinity of the influent wastewater, also coupled to the hydrocarbon dosage, exerted a huge impact on the activity of the autotrophic species. Indeed, the average $\mu_{A,max}$ of plants 1 and 2 and were significantly lower compared to what achieved in the other pilot plants. This result is in line with previous experiences highlighting that the autotrophic species are very sensitive to salinity variation of the inlet wastewater (Jang et al., 2013; Johir et al., 2013). Moreover, a significant negative impact on the specific respiration rates was observed, thus confirming the consistence with previous experiences (Mannina et al., 2016a).

Conversely, the best performance in terms of $\mu_{A,max}$ were showed by the pilot plant UCT-MBR in the phase characterized by C/N = 10; indeed, it was observed a good level of nitrification ability, with the biokinetic/stoichiometric parameters in good agreement with what reported in the technical literature (Di Trapani et al., 2011; Hauduc et al., 2011). On the other hands, the same UCT-MBR plant was characterized by a significant decrease of the system nitrification ability in the phase characterized by C/N = 5. This result could be likely related to the increased ammonia loading rate that could promote the production of free ammonia by stressing the activity of autotrophic populations.

The results of the UCT-MBMBR pilot plant (pilot plant N° 4) revealed that the autotrophic activity was more pronounced in the attached biomass, thus confirming the “specialization” of the two biomasses (suspended and attached) within a hybrid configuration, with the biofilm more affine towards the nitrification of the influent ammonia loading rate. Nevertheless, also the suspended biomass of the UCT-MBMBR pilot plant showed good nitrification activity, thus suggesting the occurrence of the “seeding” effect of nitrifiers from the biofilm to the mixed liquor, as highlighted in previous experiences (Di Trapani et al., 2013).

This result seems to be confirmed by an interesting aspect that was observed in the UCT-MBMBR pilot plant referring to the variation of the mixed liquor SRT (Figure 9a-b).

Indeed, the maximum growth rate of the suspended biomass showed an increasing trend when the SRT was decreased from indefinite value (no sludge withdrawals) to 30 and 15 days, respectively (Figure 9a). This result, apparently surprising for a pure activated sludge reactor working under the same operational conditions, is likely related to the aforementioned “seeding” effect due to the detached biofilm as well as the simultaneous growth of

the biofilm during experiments that was able to support nitrification even in the mixed liquor. Indeed, as reported in Figure 9b, a significant qualitative relationship was found between the $\mu_{A,max}$ and the biofilm concentration during experiments. As a final overview, the following Table 3 summarizes the average values of the kinetic/stoichiometric parameters achieved for the autotrophic species.

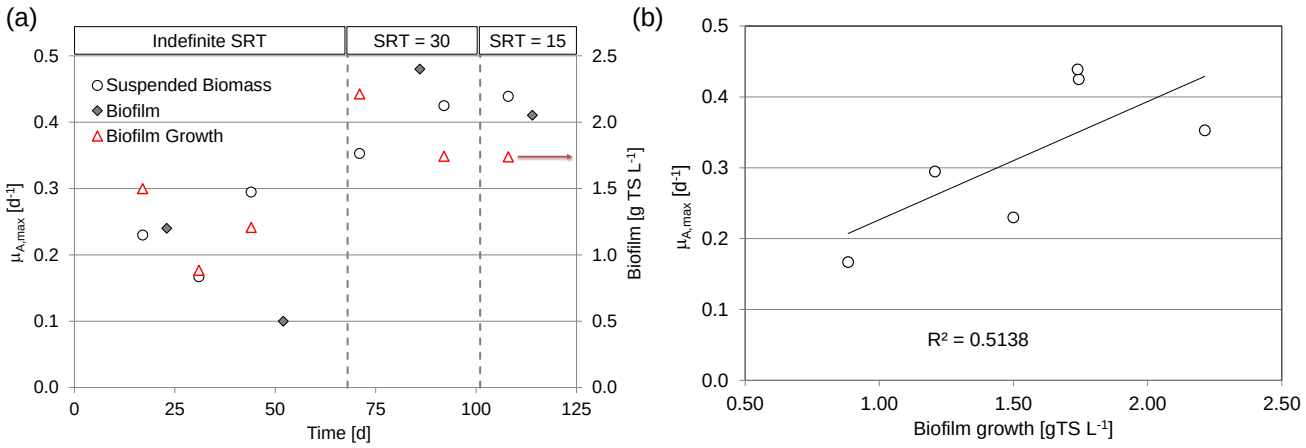


**Figure 9.** *Pattern of the $\mu_{A,max}$ and biofilm growth (a) and relationship between suspended $\mu_{A,max}$ and biofilm growth (b) in the UCT-MBMBR pilot plant*

**Table 3**. *Average values of kinetic/stoichiometric parameters for nitrifying bacteria in the investigated pilot plants (in brackets the standard deviation values).*

| Pilot plant Name | Biomass | Kinetic/Stoichiometric parameter | | | |
|---|---|---|---|---|---|
| | | $Y_A$ [mgCOD mg$^{-1}$COD] | $\mu_{A,max}$ [$d^{-1}$] | $K_{NH}$ [mg$NH_4$-N $L^{-1}$] | Max Nitrif. rate [mg$NH_4$ $L^{-1}$ $h^{-1}$] |
| SB-MBR | Suspended | 0.25 (± 0.06) | 0.15 (± 0.05) | 0.84 (± 0.63) | 1.27 (± 0.63) |
| MBR | Suspended | 0.31 (± 0.10) | 0.16 (± 0.09) | 0.67 (± 0.36) | 1.13 (± 0.61) |
| UCT-MBR C/N =10 | Suspended | 0.22 (± 0.02) | 0.39 (± 0.02) | 3.50 (± 0.52) | 4.12 (± 0.71) |
| UCT-MBR C/N =5 | Suspended | 0.29 (± 0.04) | 0.24 (± 0.05) | 1.16 (± 0.23) | 2.04 (± 0.83) |
| UCT-MBMBR | Suspended | 0.21 (± 0.06) | 0.32 (± 0.11) | 1.35 (± 0.48) | 4.40 (± 1.57) |
| UCT-MBMBR | Attached | 0.39 (± 0.15) | 0.38 (± 0.17) | 0.79 (± 0.34) | 1.44 (± 0.65) |

## 4. Conclusions

The paper presented the results of several experimental campaigns aimed at evaluating, through respirometric techniques, the biokinetic behavior of MBR systems characterized by different configurations and operational features. This study demonstrated that the configuration of the MBR process is of huge importance in the biokinetic parameter of the bacterial community and that significant differences can arise. This aspect is of paramount importance in the design phase, when the proper kinetic parameters must be used in the mathematical models. Moreover, the study revealed that the effect of specific operational conditions and/or

influent wastewater characteristics may be different or even contrasting on the activity heterotrophic or autotrophic species, thus significantly influencing the kinetic parameters. Finally, the results achieved in the present study confirmed that respirometry is a simple and powerful tool for the characterization of biomass in MBR processes and the kinetic parameters should provide a useful support in MBR design and management, as well as in MBR simulations by means of mathematical models.

## Acknowledgements

This work forms part of a research project supported by grant of the Italian Ministry of Education, University and Research (MIUR) through the Research project of national interest PRIN2012 (D.M. 28 dicembre 2012 n. 957/Ric − Prot. 2012PTZAMC) entitled “Energy consumption and GreenHouse Gas (GHG) emissions in the wastewater treatment plants: a decision support system for planning and management − http://ghgfromwwtp.unipa.it”.

## References

[1] Capodici, M., Di Bella, G., Di Trapani, D. Torregrossa, M., Viviani 2016. Respirometry for the characterization of heterotrophic biomass activity: Application to a MBR pilot plant operated with two different start-up strategies. J. Env. Eng. 142(02).

[2] Carta, F., Beun, J. J., Van Loosdrecht, M. C. M., and Heijnen, J. J. 2001. Simultaneous storage and degradation of PHB and glycogen I activated sludge cultures. Water Res., 35(11), 2693–2701.

[3] Di Trapani, D., Capodici, M., Cosenza, A., Di Bella, G., Mannina, G., Torregrossa, M., Viviani, G. 2011. Evaluation of biomass activity and wastewater characterization in a UCT-MBR pilot plant by means of respirometric techniques. Desalin. 269(1–3), 190–197.

[4] Di Trapani, D., Christensson, M., Torregrossa, M., Viviani, G., Ødegaard, H., 2013. Performance of a hybrid activated sludge/biofilm process for wastewater treatment in a cold climate region: influence of operating conditions. Biochem. Eng. J. 77, 214–219.

[5] Di Trapani, D., Di Bella, G., Mannina, G., Torregrossa, M., Viviani, G., 2014. Comparison between moving bed-membrane bioreactor (MB-MBR) and membrane bioreactor (MBR) systems: Influence of wastewater salinity variation. Bioresour. Technol. 162, 60–69.

[6] Di Trapani, D., Di Bella, G., Mannina, G., Torregrossa, M., Viviani, G., 2015. Effect of C/N shock variation on the performances of a moving bed membrane bioreactor. Bioresource Technology 189, 250–257

[7] Ekama, G.A., Siebritz, I.P., Marais, G.R., 1983. Considerations in the process design of nutrient removal activated sludge processes. Wat. Sci. Tech. 15 (3-4), 283 – 318.

[8] Gao, W.J., Han, M.N., Qu, X., Xu, C., Liao, B.Q., 2013. Characteristics of wastewater and mixed liquor and their role in membrane fouling. Bioresour. Technol. 128, 207–214.

[9] Guo, W., Ngo, H.H., Li, J., 2012. A mini-review on membrane fouling. Bioresour. Technol. 122, 27–34.

[10] Hauduc, H., Rieger, L., Ohtsuki, T., Shaw, A., Takács, I., Winkler, S., Héduit, A., Vanrolleghem, P.-A.,

Gillot, S., 2011. Activated sludge modelling: development and potential use of a practical applications database. Water Sci. Technol. 63, 2164–2182.

[11] Jang, D., Hwang, Y., Shin, H., Lee, W., 2013. Effects of salinity on the characteristics of biomass and membrane fouling in membrane bioreactors. Bioresour. Technol. 141, 50–56.

[12] Johir, M.A.H., Vigneswaran, S., Kandasamy, J., BenAim, R., Grasmick, A., 2013. Effect of salt concentration on membrane bioreactor (MBR) performances: detailed organic characterization. Desalin 322, 13–20.

[13] Judd, S. (2006). The MBR book: Principles and applications of membrane bioreactors in water and wastewater treatment, S. Judd and C. Judd, eds., Elselvier, Oxford, U.K.

[14] Judd, S.J., Judd, C., 2010. Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment, second ed. Elsevier, London, UK.

[15] Karahan-Gül, Ö., Artan, N., Orhon, D., Henze, M., van Loosdrecht, M.C.M. 2002. Respirometric assessment of storage yield for different substrates, Water Sci. Technol. 46, 345–352.

[16] Le-Clech, P., Chen, V., Fane, T.A.G., 2006. Fouling in membrane bioreactors used in wastewater treatment. J. Membr. Sci. 284, 17–53.

[17] Majewsky, M., Gallé, T., Yargeau, V., and Fischer, K. (2011). “Active heterotrophic biomass and sludge retention time (SRT) as determining factors for biodegradation kinetics of pharmaceuticals in activated sludge.” Bioresour. Technol., 102(16), 7415–7421.

[18] Majone, M., Dircks, K., Beun, J.J., 1999. Aerobic storage under dynamic conditions in activated sludge processes. The state of the art. Water Sci. Technol. 39, 61–73.

[19] Mannina G., Capodici, M., Cosenza, A., Di Trapani, D., Viviani G. (2016b). Sequential batch membrane bio-reactor for wastewater treatment: The effect of increased salinity. Bioresour. Technol. 209, 205-212.

[20] Mannina, G., Capodici, M., Cosenza, A., Di Trapani, D. (2016c). Carbon and nutrient biological removal in a University of Cape Town membrane bioreactor: Analysis of a pilot plant operated under two different C/N ratios. Chem. Eng. J. (in press), http://dx.doi.org/10.2016/j.cej.2016.03.114

[21] Mannina, G., Cosenza, A. Di Trapani, D., Capodici, M., Viviani, G. (2016a). Membrane bioreactors for treatment of saline wastewater contaminated by hydrocarbons (diesel fuel): An experimental pilot plant case study, Chem. Eng. J., 291(1), 269–278.

[22] Mannina, G., Cosenza, A., 2013. The fouling phenomenon in membrane bioreactors: assessment of different strategies for energy saving. J. Membr. Sci. 444, 332–344.

[23] Mannina, G., Di Bella, G., and Viviani, G. (2011). “An integrated model for biological and physical processes in membrane bioreactors (MBR).” J. Membr. Sci., 376(1–2), 56–69.

[24] Meng, F., Chae, S.R., Drews, A., Kraume, M., Shin, H.S., Yang, F., 2009. Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material. Water Res. 43, 1489–1512.

[25] Munz, G., Gori, R., Cammilli, L., and Lubello, C. (2008). “Characterization of tannery wastewater and biomass in a membrane bioreactor using respirometric analysis.” Bioresour. Technol., 99(18), 8612–8618.

[26] Ramdani, A., Dold, P., Gadbois, A., Déléris, S, Houweling, D., and Comeau, Y. (2012). “Biodegradation of

the endogenous residue of activated sludge in a membrane bioreactor with continuous or on-off aeration." Water Res., 46(9), 653–668.

[27] Smith, S., Judd, S., Stephenson, T., and Jefferson, B. (2003). "Membrane bioreactors—Hybrid activated sludge or a new process?" Membr. Technol., 2003(12), 5–8.

[28] Spanjers, H., Vanrolleghem, P. A., Olsson, G., and Dold, P. (1996). "Respirometry in control of the activated sludge process." Water Sci. Technol., 34(3–4), 117–126.

[29] Vanrolleghem, P.A., Spanjers, H., Petersen, B., Ginestet, P., Takacs, I., 1999. Estimating (combination of) Activated Sludge Model No. 1 parameters and component by respirometry. Water Sci. Technol. 39, 195–214.