Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1066273

57 (2016) 14414–14423
July

Taylor & Francis
Taylor & Francis Group

Two advanced biological approaches for sludge minimization from municipal wastewater treatment

Claudio Di Iaconi[a,*], Anna Laura Eusebi[b,*], Marco De Sanctis[a], Paolo Battistoni[b], Giuseppe Mininni[c]

[a]*Istituto di Ricerca Sulle Acque C.N.R, Via F. De Blasio 5, 70132 Bari, Italy, emails: claudio.diiaconi@ba.irsa.cnr.it (C. Di Iaconi), marco.desanctis@ba.irsa.cnr.it (M. De Sanctis)*
[b]*Dipartimento SIMAU, Università Politecnica delle Marche, Via Brecce Bianche 12, 60100 Ancona, Italy, emails: a.l.eusebi@univpm.it (A.L. Eusebi), p.battistoni@univpm.it (P. Battistoni)*
[c]*Istituto di Ricerca Sulle Acque C.N.R., Area della Ricerca di Roma 1, Monterotondo, Rome, Italy, email: mininni@irsa.cnr.it*

Received 29 January 2015; Accepted 22 June 2015

ABSTRACT

Two advanced biological solutions for sludge minimization in wastewater treatment are tested. The first solution, particularly suitable for new installations, is based on the application of the sequential batch biofilter granular reactor (SBBGR). The second one, mostly appropriate for existing plants, is the alternate cycles process applied in the sludge line (ACSL) of conventional activated sludge systems. The results of treating raw municipal wastewater show that the SBBGR system is able to reduce the quantity of sludge up to 80%. Furthermore, the produced excess sludge requires no longer stabilization compared with the usual aerobic/anaerobic one. As regards the ACSL process, the results obtained in the full scale have shown an observed sludge yield reduction up to 54% with an increase in the specific oxygen uptake rate up to 20 $mgO_2/gVSS/h$. Finally, applying the ACSL process low specific consumption of energy is required.

Keywords: Bioreactors; Wastewater treatment; Growth kinetics; Optimization; Sequential batch biofilter granular reactor; Alternate cycles process in the sludge line

1. Introduction

The treatment and the final disposal of the sludge produced during municipal wastewater treatment can be estimated between 350 and 750 Euros per ton of dry solids and represents up to 60% of total managing cost of the entire plant [1,2]. In Europe, from 1998 to 2005 an increase of about 40% of sludge production has been observed reaching a current annual production higher than 10 million tonnes of dry solids [3]. This scenario is expected to increase both for the progressive more stringent criteria for the effluent regulation and for the growing number of wastewater treatment plants (WWTPs). Therefore, in the near future, reducing excess sludge production will be one of the most challenging tasks for the wastewater treatment industry. In the past, different strategies have been applied to reduce the production of excess sludge from the biological treatments [4–8]. Most of these strategies attempt to shift the metabolism of organic pollutants from an anabolic to a catabolic pathway.

*Corresponding authors.

Two different innovative biological solutions exploiting this mechanism have been tested in the Routes project ("Novel processing routes for effective sewage sludge management") co-funded by the European Commission in the framework of the Seventh Framework Programme.

The first, particularly suitable for new installations, is based on the application of the sequencing batch biofilter granular reactor (SBBGR), a new biological system developed during the last decade by the Water Research Institute of the National Research Council of Italy. Thanks to its particular type of biomass growing (i.e. a mixture of biofilm and granules packed in a filling material), this system is able to enhance the biomass retention up to 10 times (compared with the conventional activated sludge systems) leading to a large reduction in the production of excess sludge. The net biomass growth rate depends from the biomass concentration and is equal to the difference between growth due to substrate consumption, considering the true yield factor, and the decay linked to endogenous metabolism, death, predation and lysis. Therefore larger the biomass concentration, smaller the net biomass growth becomes. The SBBGR technology has been applied to treat different types of wastewaters (municipal primary effluents, tannery wastewater, municipal landfill leachates and textile wastewater) obtaining low excess sludge production [9–12]. In particular, the sludge quantity usually produced in the biological unit was reduced up to 80% treating municipal primary effluent [9].

The application of the SBBGR technology for treating raw wastewater could offer interesting possibilities to maximize the reduction of the sludge production considering that 60% of the total quantity of sludge conventionally produced comes from the primary treatment stage. The potentiality of the SBBGR system for treating raw domestic sewage is evaluated in the present paper.

The second solution, particularly appropriate for existing plants, is based on the application of the alternate cycles process in the sludge line (ACSL) of conventional activated sludge system. The ACSL can be realized in a dedicated reactor (conditioning tank) where a fraction of the activated sludge (recycled from the secondary settler to the main biological basin) is exposed to cyclic different environmental conditions mainly for promoting catabolism [13]. The process is controlled on the basis of the variation of oxidation reduction potential (ORP) in anoxic/anaerobic environments. Sludge cycling between different ORP conditions has been considered one of the possible approaches to minimize the sludge growth. In fact, this mechanism was first tested by Westgarth et al. [14], who inserted an anaerobic tank in the return sludge line obtaining a 50% decrease in the sludge production. The results of the application of ACSL in a full-scale WWTP are reported in the present paper.

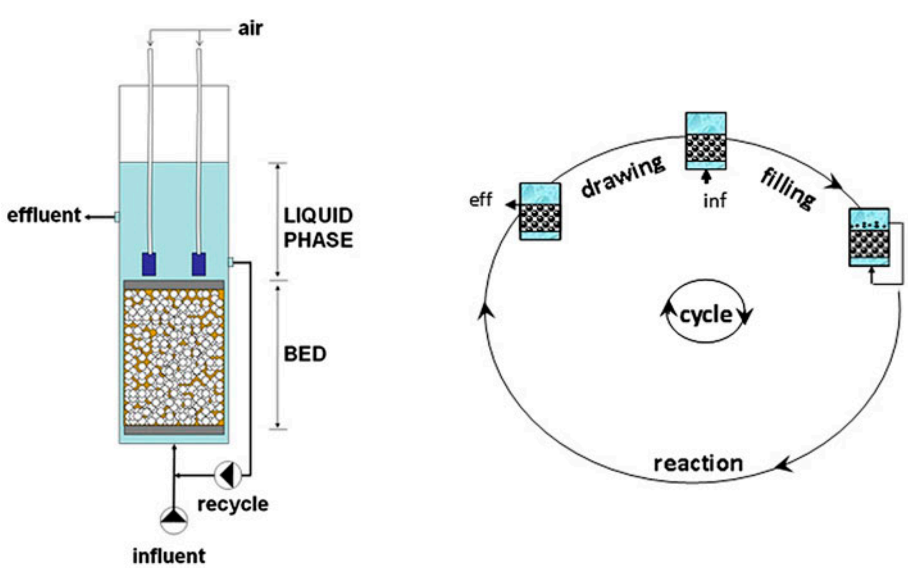

Fig. 1. Sketch (on the left) and operation (on the right) of lab-scale SBBGR.

2. Materials and methods

2.1. Sequencing batch biofilter granular reactor (SBBGR)

The SBBGR system was realized in single tank where the wastewater was fed, treated and finally discharged. The study was carried out using the lab-scale SBBGR system shown in Fig. 1.

The pilot consisted in cylindrical plexiglass reactor (geometric volume: 30 L) partially filled (fixed bed volume: 9 L) with biomass supporting material (wheel-shaped plastic elements; length: 7 mm; diameter: 10 mm; specific surface: 630 m^2/m^3; density: 0.95 g/cm^3, bed porosity: 0.75) packed between two sieves and aerated by air injection through porous stones placed close to the upper sieve. The wastewater recirculation was assured with external pumping loop through the filling material in order to obtain homogeneous distribution of substrate and oxygen. One peristaltic pump and one motorized valve provided, respectively, the filling and drawing operations. A pressure meter, set at the bottom of the reactor, measured on-line the head losses of the biofilter due to the biomass growth and to the captured suspended solids occurring in the wastewater. When a fixed set value of head loss was reached, a washing step was carried out by compressed air until the head loss was decreased down to a previously defined value. The water used for washing was collected and measured in order to calculate the specific sludge production (SSP) and to evaluate its stabilization level. The operation of the system was based on a succession of treatment cycles each consisting of three consecutive phases (see Fig. 1): filling, reaction and drawing phase. During the filling phase, a fixed volume of wastewater to be treated was added to the liquid volume retained by the reactor from the previous treatment cycle. In the reaction phase, the filled wastewater was continuously aerated (dissolved oxygen (DO) concentration was kept in the range of 5–7 mg/L) and recycled through the biomass supporting material. Finally, the treated wastewater (the same volume as the influent) was discharged by gravity from the reactor by means of a motorized valve. The operative schedule (filling, recirculation, aeration, drawing, etc.) was completely automated by a programmable logic controller. During the first four - months, the experimental activities were aimed at generating the biomass typical of the SBBGR system (i.e. a mixture of biofilm and granules packed in the filling material) by a gradual shift of the attached biomass fraction from the biofilm to granules. In particular, taking into account the know-how about the SBBGR gained in previous studies [15,16], the hydraulic loading to the plant was adjusted in order to have an applied organic loading in the range 0.2–0.4 gCOD/L_{bed} d. After the biomass generation, the hydraulic residence time (HRT) of the plant was reduced from 1.8 down to 0.9 d by increasing the influent hydraulic loading in order to assess the treatment capability and the sludge production of the SBBGR system. The treatment performances of the SBBGR were evaluated over a period of 400 d by measuring several influent and effluent parameters. In particular, chemical oxygen demand (COD), total (TSS) and volatile (VSS) suspended solids, total Kjeldahl nitrogen (TKN), ammonia (NH_3), nitric (N-NO_3) and nitrous (N-NO_2^-) nitrogen, and phosphorous were determined using standard methods [17]. Total nitrogen (TN) was calculated as the sum of TKN and oxidized nitrogen.

The SSP was calculated dividing TSS leaving the system (i.e. TSS discharged with the effluent + TSS removed during the washing operation) by the amount of COD removed during the interval between two washing operations. Head losses at the bottom of the bed were monitored through a pressure meter.

The biomass concentration in the reactor was determined with representative microbial samples from the biological bed. The sampled volume of the bed was evaluated by counting the carrier elements ($n_{carriers}$) and relating them to the number of carrier elements per litre of bed (1,023). The sludge present on the removed carriers was collected in a known volume of tap water (V_{sludge}), TSS and VSS were measured. The sludge concentration in the reactor bed could be calculated according to Eq. (1).

$$\text{Biomass concentration } [g_{TSS}/L_{bed}] = \frac{\text{TSS } [g/L] \cdot V_{sludge}\ [L]}{\frac{n_{carriers}}{1{,}023}} \tag{1}$$

The sludge age (θ_c) was calculated using the following Eq. (2.

$$\theta_c = \frac{\text{Biomass concentration } (gTSS/L_{bed}) \times \text{bed volume } (L_{bed})}{\text{SSP } (gTSS/gCOD_{removed}) \times \text{hydraulic loading } (L/d) \times COD_{removed}\ (gCOD_{removed}/L)} \tag{2}$$

2.2. Alternate cycles process in sludge line (ACSL)

The ACSL takes place in a dedicated reactor (conditioning tank) which receives a fraction of the activated sludge recycled from the secondary settler to the main biological basin. The tank is equipped with probes used for registering the DO and ORP. The probes permit the automatic control of the process. Furthermore, air supply system and mixing devices are installed to perform the aerobic and anaerobic phases. Two main ranges of the ORP are set, below −150 mV, and from −150 to +50 mV, for selecting facultative anaerobic biomass and facultative aerobic biomass, respectively. In the reactor, the oxygen supply is alternated with anaerobic phases: the ORP value increases until the aeration is stopped (average DO 1.2 ± 0.2 mg/L) then it decreases. A pair of these two phases constitutes one cycle. An automatic control system for local and remote control allows the duration of the cycle in each range to be set as percentage of the ORP (ORP%). The ACSL process was implemented at a full-scale plant of 27,500 PE (population equivalent) characterized by an activated sludge process with two aerobic sludge stabilization basins. One of these basins (with a volume of 629 m^3) was converted in the conditioning reactor, whereas the other was maintained in its original configuration (see Fig. 2). In order to enhance nitrogen removal, the activated sludge basin of the biological stage of the plant was converted to a continuous aerobic/anoxic process (AC) according to Eusebi et al. [18]. The experimentation was carried out for nine months, of which the first three months were required to start-up the process and to achieve steady-state conditions. The hydraulic retention time of the ACSL reactor was regulated at 4 d. Overall, the biomass in the ACSL reactor was maintained for 45% of the time at ORP values lower than −150 mV and for 55% of the time at ORP values between −150 and +50 mV. The number of daily cycles carried out in the ACSL reactor was from 10 to 30 no cycles/d, indicating the rate of the change of the two ORP ranges. This rate was the consequence of the respirometric characteristics of the influent sludge, of the HRT and of the environmental percentages imposed. The application of the oxic/anoxic process in the activated sludge reactor of the plant for enhancing the nitrogen removal also led to a variation in ORP in the main biological basin of the plant. In particular, the ORP values in the main basin were higher than +50 mV during the aerobic phases dropping to the range of −150 and +50 mV during the anoxic phase. Average influent and effluent samples and grab sludge samples were collected from the different reactors (biological, ACSL and stabilization unit) and characterized in terms of the main parameters according to standard methods [17]. The heterotrophic growth yield Y_h (kgVSS/kgCOD) was calculated once a week in both ACSL and activated sludge reactor according to the procedure proposed in Marais and Ekama [19]. Specific oxygen uptake rate, SOUR (mgO_2/gVSS h), was tested dividing each Y_h profile by the biomass concentration (in terms of mixed liquor volatile suspended solids; MLVSS). In particular, the maximum value of SOUR (maximum value during the sodium acetate respiration) was used to compare the exogenous behaviour of the biomass over time. The

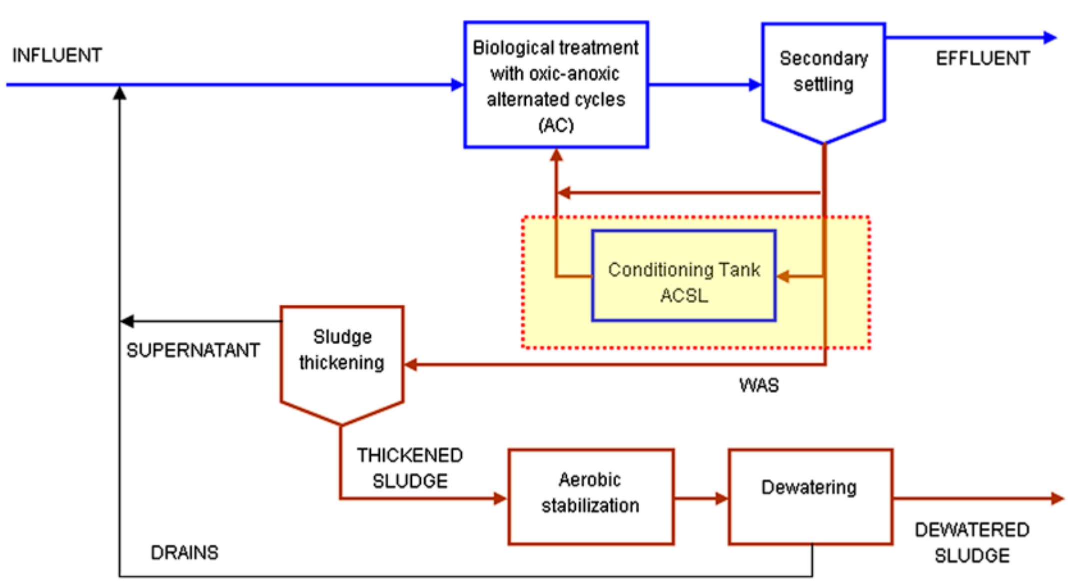

Fig. 2. Sketch of the WWTP upgraded with AC and ACSL.

sludge production was evaluated on monthly basis, in terms of the amount of both dewatered volatile solids produced per person and per year (P_x—kgVSS/PE y) and volatile solids produced per amount of COD removed (Y_{obs}—kgVSS/kgCOD). The Yobs was determined in the actual and in the expected conditions. The actual Y_{obs} was compared with the expected one, estimated on the basis of the effective SRT (sludge retention time equal of 12 ± 3 d), the endogenous decay rate (k_d equal to 0.04 ± 0.01 1/d) and the amount of substrate removed.

3. Results and discussion

3.1. SBBGR performance

The typical biomass of the SBBGR was obtained towards the end the fourth month. After biomass generation, the HRT of the plant was reduced stepwise (from 1.8 down to 0.9 d) by increasing the hydraulic loading applied to the plant in order to evaluate the effectiveness of the SBBGR on organic load removal. The plant performances recorded at the minimum investigated HRT (i.e. 0.9 d) are summarized in Table 1, in terms of average values ± standard deviation and value range.

The COD removal efficiency was always higher than 83.8% (on average 90.5%) with a residual concentration in the effluent lower than 72 mg/L (on average 41 mg/L) independently from the influent COD value, which ranged from 260 up to 979 mg/L, and from the organic loading rate applied (OLR) to the plant, which was always higher than 2.67 gCOD/L_{bed} d. This result can be ascribed to the great operational flexibility and stability of the SBBGR system in response to changes in wastewater composition. The data of the total suspended solids show that the concentration in the effluent was constantly lower than 25 mg/L (on average, 10 mg/L) with average removal efficiencies higher than 95% independently from the influent TSS values from 83 to 586 mg/L.

Referring to TKN and ammonia, the results show that the plant was able to remove, respectively, on an average 96.3 and 98.0% of TKN and ammonia content with residual concentrations in the effluent of 2.3 mgTKN/L and 1.0 mgNH_4-N/L thus indicating a stable nitrification process despite the large variation of OLR value applied to the plant (i.e. from 0.71 to 2.67 gCOD/L_{bed} d). The nitrification process was not greatly affected by the OLR applied. This result has to be considered of great relevance if compared with data of the conventional biological treatment systems

Table 1
SBBGR treatment performance (in terms of average values ± standard deviation and value range) recorded at HRT of 0.9 d

Parameter		Mean value (±st. dev.)	Value range
OLR	(gCOD/L_{bed} d)	1.35 (±0.61)	0.71–2.67
Influent COD/N		8.8 (±5.5)	3.3–27.3
COD	Influent (mg/L)	495 (±224)	260–979
	Effluent (mg/L)	41 (±12)	23–72
	Removal efficiency (%)	90.5 (±3.8)	83.8–96.9
TSS	Influent (mg/L)	292 (±139)	83–586
	Effluent (mg/L)	10 (±6)	3–25
	Removal efficiency (%)	95.5 (±3.4)	85.8–99.4
VSS	Influent (mg/L)	253 (±133)	65–580
	Effluent (mg/L)	6 (±4)	2–18
	Removal efficiency (%)	96.5 (±2.8)	86.7–99.5
TKN	Influent (mg/L)	66.0 (±19.6)	35.9–124.1
	Effluent (mg/L)	2.3 (±1.5)	0.4–7.5
	Removal efficiency (%)	96.3 (±2.1)	90.7–99.4
NH_4^+	Influent (mgN/L)	42.4 (±17.9)	21.0–89.6
	Effluent (mgN/L)	1.0 (±1.7)	0–6.4
	Removal efficiency (%)	98.0 (±3.5)	88.0–100
TN	Influent (mg/L)	66.3 (±19.6)	35.9–124.4
	Effluent (mg/L)	9.8 (±4.4)	1.7–17.5
	Removal efficiency (%)	85.3 (±6.1)	72.8–95.4
P_{tot}	Influent (mg/L)	2.5 (±1.5)	0.2–4.2
	Effluent (mg/L)	2.3 (±0.8)	1.4–3.9
	Removal efficiency (%)	12.7 (±16.2)	0–40.1

based on activated sludge processes where a strong competition for DO exists between autotrophic and heterotrophic bacteria [17].

Furthermore, the data in Table 1 seem to indicate that no significant correlation there is between TKN removal efficiency and carbon to nitrogen (COD/N) ratio in the influent wastewater of the plant from 3.3 up to 27.3. In fact, high COD/N values in wastewater lead to an overgrowth of heterotrophic micro-organisms with consequent nitrification inhibition [20,21]. In fact, Carrera et al. [22] observed that nitrification rates decreased up to 79% when the influent COD/N increased from 0.71 to 3.4 during the treatment of industrial wastewater with high-strength ammonium applying the modified Ludzack–Ettinger pilot plant configuration. Therefore, the results obtained in the present study (i.e. no impact on nitrification efficiency for temporary influent COD/N values even higher than 20) should be considered as particularly interesting, all the more so, since they were obtained using a real raw wastewater (i.e. without any pretreatment).

Regarding nitrogen removal, TN data highlight also the presence of denitrification process with average removal efficiencies of 85.3% (with peaks up to 95.4%) and residual effluent concentrations of 9.8 mg/L. The process was somewhat stable despite the influent COD/N ratio which was sometimes lower than 6 (down to 3.3). The major contribution to denitrification has to be ascribed to the produced carbonaceous substrate by biomass decay because of the high biomass age and concentration makes.

The sludge production, as reported in the material and methods, was calculated dividing TSS leaving the system by the amount of COD removed during the interval between two washing operations. In the SBBGR system, washing operations regulate the sludge age (they play the same role as the sludge wasting flow rate in conventional activated sludge systems) which is the main factor allowing the excess sludge production to be reduced in this system. The obtained values defined an average SSP of 0.150 kgTSS/kgCOD.

This value is much lower (up to 80% lower) than those reported in the literature for municipal WWTPs) [3,23]. Acceptable level of stabilization of excess sludge was also obtained (VSS/TSS ratio of about 0.55) not determining further or longer stabilization process. This result is particularly relevant for small WWTPs where the sludge produced is sometimes transported to a larger treatment plant where the facilities for sludge treatment are available.

The low sludge production value can be related to the high sludge age (a value of 253 d was calculated by Eq. (2)). Therefore the micro-organisms spend much time in the endogenous metabolism phase where the biomass decay rate is high and the biomass production rate is low [9].

Sludge concentration in the reactor was on average of 46.0 $gTSS/L_{bed}$. However, a stratified distribution was observed with the higher concentration at the bottom (52 $gTSS/L_{bed}$) and the lower at the top (41 $gTSS/L_{bed}$). This result is the consequence of the operation of the reactor in the upflow configuration because the bacteria growth is the highest at the filter inlet where the organic loading is the most elevated. The contents of nitrogen and phosphorous of the biomass were, respectively, 0.021 gN/gTSS and 0.007 gP/gTSS.

According to the low obtained production of the sludge, the plant showed low phosphorus removal efficiencies (on average 12.7%—Table 1). The highest values of the recorded removal efficiency (i.e. 40.1%) could be related to the filtering capability of SBBGR system against suspended solid particles containing phosphorus.

On the basis of the exposed results, at full scale is expected a significant reduction (i.e. about 80%) of the cost due to sludge treatment and disposal which accounts for about 50% of the total costs of the entire WWTP. Furthermore, considering that the specific electric energy consumption of SBBGR treatment is only 10–15% higher than that of conventional activated sludge systems, a total saving of about 25–35% should be expected by using SBBGR technology.

3.2. *Alternate cycles process in sludge line (ACSL)*

The ACSL process was implemented in one full scale municipal WWTP with a design capacity of 27,500 PE. This plant is characterized by long periods of overloading conditions due to the seasonal tourist activities. In particular, Fig. 3 shows during the experimental period the profile of the population equivalent and the organic loading rate (F/M) specific for biomass. The average values of the actual population equivalent (calculated on the basis of the COD values) and of the F/M were, respectively, 33,668 ± 11,479 PE and 0.28 ± 0.10 kgCOD/kgMLVSS d. Despite the overloading conditions of the plant, the removal efficiencies of 95, 98 and 84% were recorded for COD, TSS and TN, respectively, during ACSL application, with residual concentrations in the final effluent much lower than the discharge limits.

The evaluation of the activation of catabolism promotion and anabolism demotion during the ACSL process was an important experimental objective of the study, since alternating bacterial growth conditions

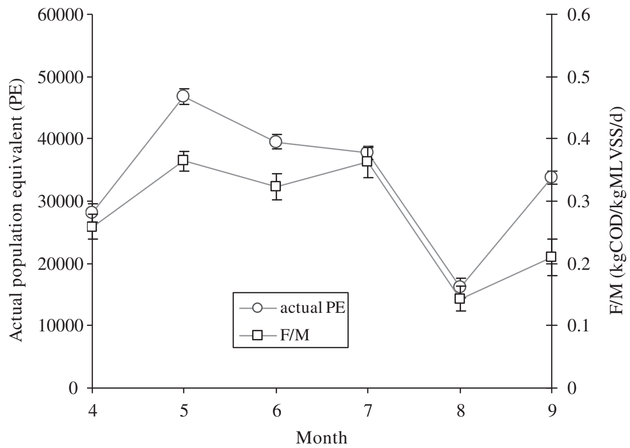

Fig. 3. Actual average population equivalent and biomass organic loading rate during the experimental period (the bars indicate the deviation standard) of ACSL application.

have been found to improve metabolic uncoupling [24]. In this sense, in the anoxic/anaerobic ACSL reactor the bacteria are focused on the maintenance of the metabolism considering the low production of adenosine triphosphate for the absence both of substrate and of efficient electron acceptors (e.g. oxygen). The sludge reduction occurs when the biomass is returned to the biological basin. In fact, in the main reactor the bacteria replenish, preferentially, the stored energy instead of synthesis of new cells. In this direction, the specific respirometric study of the heterotrophic coefficients (Y_h) in the biological (oxic/anoxic phases) and in the ACSL reactors (anoxic/anaerobic phases) was performed at 20°C and at the same F/M (acetate feed/MLVSS). The results obtained (Fig. 4(a)) show that the two reactors have the same Y_h trend with values ranging from 0.433 to 0.719 kgVSS/kgCOD, for the biological reactor, and from 0.339 to 0.783 kgVSS/kgCOD, for

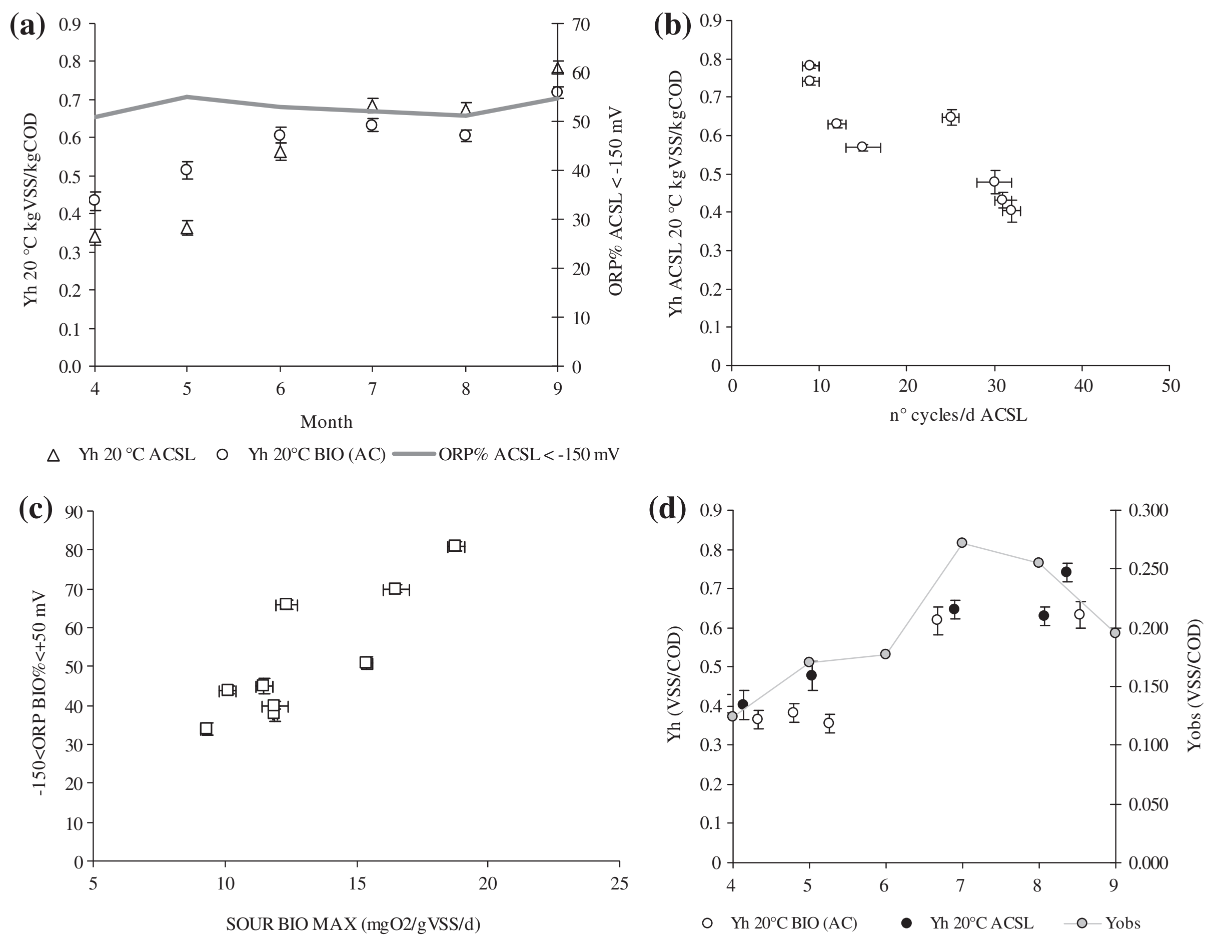

Fig. 4. Average values of the respirometric parameters during the experimental period; the bars indicate the deviation standard. (a) Y_h at 20°C in biological basin (BIO) and in ACSL reactor (ACSL), and ORP% (<−150 mV) in the ACSL reactor for each experimental month; (b) Y_h at 20°C in ACSL reactor as a function of daily cycle number; (c) maximum SOUR of biological basin (SOUR BIO MAX) as a function of ORP% (−150 mV < ORP < +50 mV); (d) Y_h at 20°C in biological basin (BIO) and in ACSL reactor (ACSL), and actual Y_{obs}.

the ACSL reactor. Moreover, the continuous increase in the heterotrophic growth yield seems not to be linked to the ORP% in the ACSL reactor maintained for 55% of the time at ORP values lower than −150 mV (Fig. 4(a)). On the contrary, the daily cycle number carried out in ACSL reactor greatly affects the Y_h data. In fact, Fig. 4(b) clearly indicates a decrease in the heterotrophic growth coefficient in correspondence to the increase in the number of the variations in environmental conditions (i.e. of the increase in the number of cycles carried out per day). This result is in agreement with the ones obtained from Jung and Tanji [25] who found that the sludge quantity was greatly reduced when aerobic and anaerobic conditions were alternated in short intervals. In order to evaluate the metabolic uncoupling mechanism, the specific oxygen uptake rate in the biological reactor was also determined. In fact, the feasting/fasting conditions between the ACSL reactor and the main water line induce a sharp increase in the SOUR [26]. This aspect indicates the high levels of substrate oxidation stimulated by the fasting condition in the ACSL reactor. Moreover, in the biological unit the main AC process determines additional ORP variations, which, clearly, are strictly related to the influent load of nitrogen and carbon instead of the result of any action to reduce sludge. The enhancing of anoxic conditions in the biological reactor (−150 mV < ORP% < +50 mV) coupled with the ACSL anoxic/anaerobic fasting environments determines the increase in the SOUR values. In fact, the obtained results (see Fig. 4(c)) show the growth of the maximum SOUR values from 9 to 18.7 mgO_2/gVSS h which seems to be directly related to the enhancement of the anoxic ORP% (−150 mV < ORP < +50 mV) in the main biological reactor (from 35 to 80%). Finally, for an explicative period, respirometric tests of both the biological and the ACSL reactors were compared with the solids mass balance values expressed as real Y_{obs}. Synchronous trends were found between the three parameters (Fig. 4(d)). The data shown in this figure indicate that the Y_h is an important and faster marker of the variations of the actual Y_{obs} in the plant permitting the prediction of the general growth behaviour of the biomass without requiring the long waiting period needed to obtain data for the solids mass balance.

The mass balances and the SSP were calculated for each experimental month. The expected and actual Y_{obs} values with their percentages of relative reduction are shown in Fig. 5(a). Average actual and expected Y_{obs} values of 0.183 ± 0.040 and 0.307 ± 0.079 kgVSS/kgCOD, respectively, were calculated. Therefore (Fig. 5(a)) the reduction percentage varied in the range from 36 to 54%. Fig. 5(b) shows the expected and actual P_x values with the relative reduction percentage calculated for each experimental month. The actual SSP values (actual P_x) show the same trend of the actual Y_{obs}. The average value of 7.3 ± 1.7 kgVSS/PE y is calculated for the actual P_x; this value is about 40% lower than the expected one (i.e. 12.1 ± 3.5 kgVSS/PE y). Furthermore, the sludge production is further reduced when the anoxic ORP% (i.e. −150 mV < ORP % < +50 mV) in the biological AC reactor increased.

Finally, the evaluation of the specific consumption of the electric energy related to the ACSL reactor (for the management of the air supply and of the electromechanical device) defined a value of 0.007 kW h/PE d.

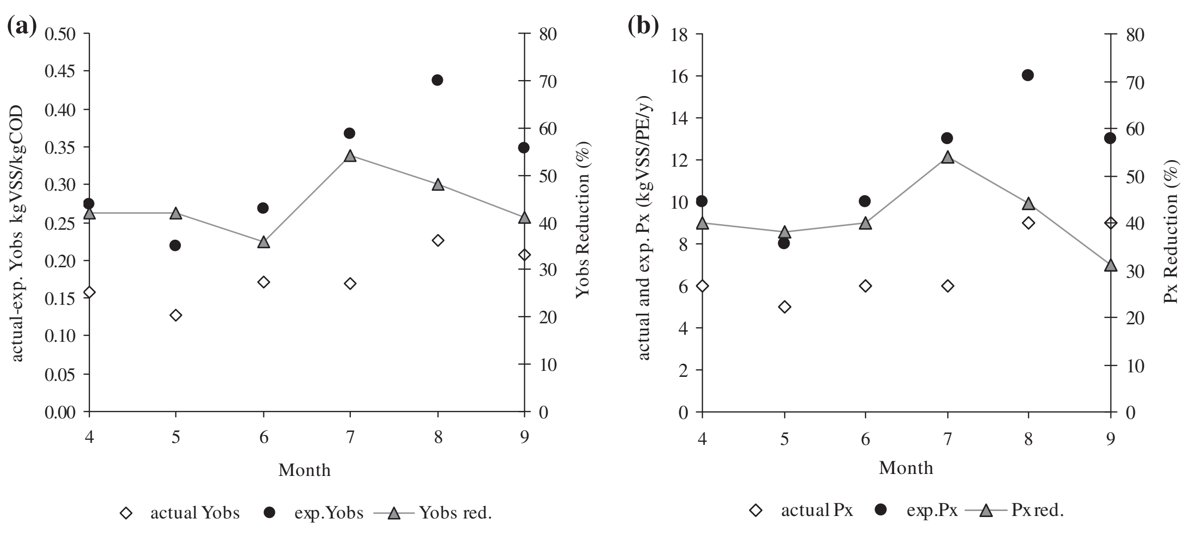

Fig. 5. Actual and expected Y_{obs} and P_x values for each experimental month for the ACSL process (a) actual and expected Y_{obs} and relative reduction percentage; (b) actual and expected P_x and relative reduction percentage.

This cost is only the 5% of the energy consumption of the entire WWTP. Considering the energetic operative costs evaluated also in other full-scale plants [13] the net saving is equal about to 96€ for ton of not produced sludge.

4. Conclusions

The present paper was aimed to the evaluation of the effectiveness of two advanced biological solutions for reducing the sludge production from the wastewater treatment.

Regarding the first solution, based on an innovative biological system (SBBGR-sequencing batch biofilter granular reactor), the results obtained during the treatment of raw domestic sewage have shown that the proposed system is able to perform in a single stage the entire wastewater treatment train (i.e. primary and secondary treatment) carried out in conventional plants and to assure removal efficiencies higher than 90% for the COD, total suspended solids and nitrogen. Furthermore, the SBBGR has been able to reduce up to 80% the quantity of sludge produced usually in the conventional WWTPs. In addition to the low amount of the excess biomass, the sludge produced requires aerobic/anaerobic stabilization no longer than the traditional one.

For the second solution (based on the application of the alternate cycles process in the sludge line, ACSL, of the conventional activated sludge systems), the results obtained in the full scale have shown that the proposed process is able to reduce the observed sludge yield up to 54%. Furthermore, an increase in the specific oxygen uptake rate in the biological reactor was recorded (up to 20 $mgO_2/gVSS\ h$) confirming that the application of ACSL process enhancing the substrate utilization rate. Finally, a low energy demand is required by ACSL process (i.e. 5% of the energetic consumption of the entire WWTP).

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement no 265156 (ROUTES project).

References

[1] P. Ginestet, Comparative Evaluation of Sludge Reduction Routes. European Water Research, IWA Publishing, London, 2007.
[2] N.J. Horan, Biological Wastewater Treatment Systems, Wiley, Chichester, 1990.
[3] P. Foladori, G. Andreottola, G. Ziglio, Sludge Reduction Technologies in Wastewater Treatment Plants, IWA Publishing, London, 2010.
[4] A. Canales, A. Pareilleux, J.L. Rolls, G. Goma, A. Huyard, Decreased sludge production strategy for domestic wastewater treatment, Water Sci. Technol. 30 (1994) 96–106.
[5] G.H. Chen, H.K. Mo, Y. Liu, Utilization of a metabolic uncoupler, 3,3´,4´,5-tetrachlorosalicylanilide (TCS) to reduce sludge growth in activated sludge culture, Water Res. 36 (2002) 2077–2083.
[6] E.W. Low, H.A. Chase, Reducing production of excess biomass during wastewater treatment, Water Res. 33 (1999) 1119–1132.
[7] Y. Wei, R.T. Van Houten, A.R. Borger, D.H. Eikelboom, Y. Fan, Minimization of excess sludge production for biological wastewater treatment, Water Res. 37 (2003) 4453–4467.
[8] H. Yasui, M. Shibata, An innovative approach to reduce excess sludge production in the activated sludge process, Water Sci. Technol. 30 (1994) 11–20.
[9] C. Di Iaconi, M. De Sanctis, S. Rossetti, R. Ramadori, SBBGR technology for minimising excess sludge production in biological processes, Water Res. 44 (2010) 1825–1832.
[10] C. Di Iaconi, G. Del Moro, M. De Sanctis, S. Rossetti, A chemically enhanced biological process for lowering operative costs and solid residues of industrial recalcitrant wastewater treatment, Water Res. 44 (2010) 3635–3644.
[11] C. Di Iaconi, S. Rossetti, A. Lopez, Effective treatment of stabilized municipal landfill leachates, Chem. Eng. J. 168 (2011) 1085–1092.
[12] A.M. Lotito, C. Di Iaconi, U. Fratino, A. Mancini, G. Bergna, Sequencing batch biofilter granular reactor for textile wastewater treatment, New Biotechnol. 29 (2011) 9–16.
[13] C. Troiani, A.L. Eusebi, P. Battistoni, Excess sludge reduction by biological way: From experimental experience to a real full scale application, Bioresour. Technol. 102 (2011) 10352–10358.
[14] W. Westgarth, F. Sulzer, D. Okun, Anaerobiosis in the activated sludge process, in: Second International Advances in Water Pollution Research Conference (IAWPRC), August 1964, Tokyo Japan, pp. 43–55.
[15] C. Di Iaconi, R. Ramadori, A. Lopez, R. Passino, Hydraulic shear stress calculation in a sequencing batch biofilm reactor with granular biomass, Environ. Sci. Technol. 39 (2005) 889–894.
[16] C. Iaconi, G. Moro, A. Lopez, R. Ramadori, The essential role of filling material in aerobic granular biomass generation in a periodic submerged biofilter, World Rev. Sci. Technol. Sustain able Dev. 6 (2009) 144–155.
[17] APHA, AWWA, WEF Standard Methods for the Examination of Water and wastewater, twenty-first ed., American Public Health Association, Washington, 2005.
[18] A.L. Eusebi, G. Carletti, E. Cola, F. Fatone, P. Battistoni, Switching small WWTPs from extended to intermittent aeration: process behaviour and performances, Water Sci. Technol. 58 (2008) 865–872.

[19] G.v.R. Marais, G.A. Ekama, The activated sludge process Part I—Steady state behaviour, Water SA 2 (1976) 163–200.
[20] K. Hanaki, C. Wantawin, S. Ohgaki, Effects of the activity of heterotrophs on nitrification in a suspended-growth reactor, Water Res. 24 (1990) 289–296.
[21] J. Hu, D. Li, Q. Liu, Y. Tao, X. He, X. Wang, X. Li, P. Gao, Effect of organic carbon on nitrification efficiency and community composition of nitrifying biofilms, J. Environ. Sci. 21 (2009) 387–394.
[22] J. Carrera, T. Vicent, J. Lafuente, Effect of influent COD/N ratio on biological nitrogen removal (BNR) from high-strength ammonium industrial wastewater, Process Biochem. 39 (2004) 2035–2041.
[23] J.R. Schultz, B.A. Hegg, K.L. Rakness, Realistic sludge production for activated sludge plants without primary clarifiers, J Water Pollut. Con. F 54 (1982) 1355–1360.
[24] F. Quan, Y. Anfeng, C. Libing, C. Hongzhang, X.H. Xing, Mechanistic study of on-site sludge reduction in a baffled bioreactor consisting of three series of alternating aerobic and anaerobic compartments, Biochem. Eng. J. 67 (2012) 45–51.
[25] S.-J. Jung, U. Tanji, Effect of intermittent aeration on the decrease of biological sludge amount, Biochem. Eng. J. 27 (2006) 246–251.
[26] X.D. Hao, Q.L. Wang, J.Y. Zhu, M.C.M. Van Loosdrecht, Microbiological endogenous processes in biological wastewater treatment systems, Crit. Rev. Environ. Sci. Technol. 40 (2010) 239–265.