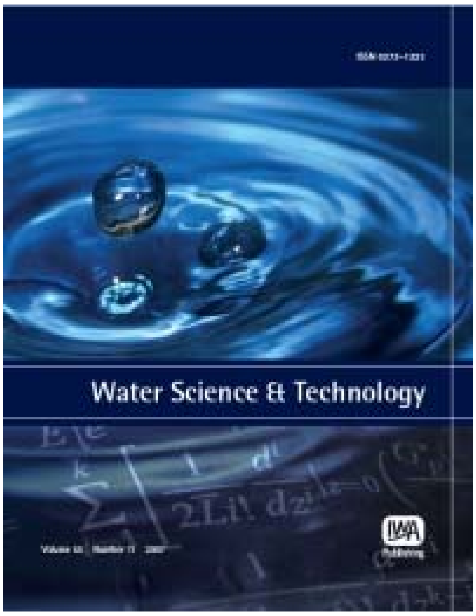
Water Science & Technology

Water Science & Technology—WST | 62.4 | 2010

Technical and experimental evaluation of an innovative decentralized technology for the municipal wastewater treatment in the city of Rome

Agostina Chiavola, Piero Sirini and Sandro Cecili

ABSTRACT

The present paper shows the results obtained through an experimental activity carried out on a pilot-scale plant using an innovative technology which couples the granular aerobic sludge with the sequencing batch process. Treatment efficiency and operation costs were evaluated in order to assess feasibility of this new technology for the upgrading of the existing continuous flow activated sludge treatment plant located in Casal Monastero, a decentralized area of the City of Rome. During start-up (about 3 months), the granular aerobic sludge was developed by controlling the dissolved oxygen concentration, the value of pH and the up-flow velocity. Besides, the influent organic loading was progressively increased starting from 0.1 kg/m^3 d up to 0.9 kg/m^3 d. In order to improve nitrogen removal, an anoxic phase was temporary added to the operative cycle. Complete development of the granular sludge determined an appreciable improvement of the denitrification process which allowed to eliminate the anoxic phase. At regime conditions, the plant was operated with 3 daily cycles, each one of 8 h. The new system showed a reduced sludge production (of about 20–35%) as compared to the existing plant, along with high removal efficiency of both Chemical Oxygen Demand (COD) and nitrogen. However, the operation was discontinuous and strictly related to the strength of the granular sludge. Therefore, a careful monitoring is recommended in order to control operation and performance of this new system.

Key words | biofilter, BIOSEQ, chemical oxygen demand, granular sludge, nitrogen, sequencing batch reactor

Agostina Chiavola (corresponding author)
Department of Hydraulics, Transportation and Roads,
University of Rome Sapienza,
Via Eudossiana 18,
Rome 00184,
Italy
E-mail: *agostina.chiavola@uniroma1.it*

Piero Sirini
Department of Civil Engineering,
University of Florence,
Via Santa Marta 3,
Florence 50139,
Italy
E-mail: *p.sirini@tiscalinet.it*

Sandro Cecili
Acea Ato 2 S.p.A.,
Piazzale Ostiense 2,
Rome 00153,
Italy
E-mail: *sandro.cecili@aceaspa.it*

INTRODUCTION

The continuous flow activated sludge plants still represent the most widely diffused wastewater treatment process, at least in Italy. This technology is well known and offers high reliability. Due to the increasing urbanization, the volumes to be treated rise continuously thus creating the need for upgrading the existing plants. Besides, the legislation poses new and more stringent requirements on the effluent quality in order to protect the natural sources. The high footprint of the existing plants and the limited available space urge upon to adopt alternative technologies which might offer higher and more stable treatment efficiency, flexibility, reduced environmental impact along with limited costs. Another urgent issue that the utilities must face is represented by the excess sludge management which can account for up to 50–60% of the total costs of the plant. Therefore, the new technologies should also allow to reduce the expenses associated to this issue.

Much interest has been paid to attached biomass systems since they operate at higher biomass density and therefore allow an increase in applicable organic loadings; besides, the longer hydraulic residence time favour the endogenous metabolism with reduced sludge production.

doi: 10.2166/wst.2010.332

A more recent application of the attached biomass is represented by the Sequencing Batch Biofilm Granular Reactor (SBBGR) which couples flexibility of the Sequencing Batch Reactor (SBR) to high biomass densities typical of the biofilm processes (such as the Sequencing Batch Biofilm Reactor, SBBR) (Dollerer & Wilderer 1996; Arnz *et al.* 2000; Wilderer *et al.* 2001; Wilderer & McSwain 2004; Liu & Tay 2006; Farabegoli *et al.* 2008; Li *et al.* 2008). Particularly, in this case the attached biomass grows in the form of granules which determines even higher concentrations in the reactor (up to 15 g/L). The process was recently developed by the Water Research Institute of the Italian National Research Council (IRSA-CNR) (Di Iaconi *et al.* 2005, 2007, 2008*a*,*b*).Differently from a biofilter and similarly to a SBR, the SBBGR works through a discontinuous process: for instance, each operating phase of the biological treatment process (such as carbon removal, nitrification, denitrification) take place within the same unit based on a time-sequence. Since microorganisms grows in a granular and attached phase, differently from a SBR the settlement phase is not required in a SBBGR and the detached biomass and solids are retained within the reactor during the draw phase by the packing material. The influent is applied upward and the effluent is usually recirculated from the top to the bottom of the reactor to ensure a more homogeneous distribution of the substrate and biomass along the bed depth. The hydrodynamic shears due to the upflow velocity are known to play a key role in the granule formation which usually takes place during reactor's start-up (Di Iaconi *et al.* 2008*a*,*b*). The SBBGR offers several advantages such as: higher removal rates, reduced sludge production, higher stability against shock loadings.

The present paper shows the results of an experimental activity carried out on the pilot-scale plant BIOSEQ (Sequential Biofilter) in the frame of a cooperation between Laboratori S.p.A. (belonging to the Company ACEA Ato 2 S.p.A., which manages the entire water cycle of the city of Rome), and CSA (Centro Studi Ambientali, Italy) which provided the plant. The BIOSEQ system is based on the SBBGR technology. Its main feature is represented by the fact that air is not provided directly in the biofilter (which functions as the biological reactor): instead, air blowing occurs in a distinct unit, referred to as the aerator, and then is delivered to the reactor via the liquid effluent recirculation which takes place continuously between the two units. Besides, influent and air streams are applied upward and co-currently in the reactor.

The general aim of the study was to evaluate feasibility of the BIOSEQ technology to upgrade the existing wastewater treatment plant located in Casal Monastero (Rome) which uses the traditional scheme of the activated sludge (AS) reactor followed by secondary settlement and chlorination. The study mainly focused on the achievable treatment efficiency for both carbon and nitrogen, at different influent organic loadings; besides, the main physical and biological characteristics of the granular sludge were determined.

METHODS

Pilot-plant

The BIOSEQ pilot-plant was located in Casal Monastero (Rome) and fed with the same influent delivered to the full-scale plant, after screening and degritting. Table 1 shows the average influent characteristics. The full-scale wastewater treatment plant of Casal Monastero consists of two parallel lines and is composed by the following units: pumping station, fine screens and static degritting chamber, activated sludge reactor, secondary settlement, chlorination and filtration, sludge storage tank. It has been originally designed to serve about 6,000 equivalent inhabitants (EI); however, progressive population growth has posed the urgent need to increase the available treatment capacity.

Table 1 | Average influent characteristics

Parameter	Concentration (g/m^3)
BOD	175
COD	435
Filtrate COD*	130
TSS	235
VSS	188
Total nitrogen, N_{tot}	58
Filtrate N_{tot}*	47
NH_4^+-N	46
P_{tot}	7.5

*At 0.45 μm.

The BIOSEQ plant is composed by two sequential units, having different functions and dimensions, referred to as the biofilter reactor and the aerator, respectively. Table 2 lists the main dimensions of these units, whereas Figure 1 shows a picture of the BIOSEQ system. The biofilter represents the biological reactor, has lower dimensions, and contains the filling material which is used for the granular biomass growth. The influent flows upward in the biolfilter reactor through the filling bed. Aeration is provided directly to the liquid stream only in a separate unit, referred to as the aerator; then, through liquid recirculation, air flow is transferred also to the reactor.

The plant is completely automated, with the control of the main operating parameters, such as dissolved oxygen concentration (DO), recirculation flowrate, pH and temperature.

A typical operating cycle starts with the fill phase, during which the influent is delivered to the aerator tank where it is added to a residual volume from the previous operating cycle (V_{RES}). The liquid level in the aerator rises up progressively; when the prefixed volume V_1 is reached, air blowing starts (static feed). After few minutes, also the recirculation pump switches on and a constant wastewater flowrate is being transferred from the aerator to the biofilter reactor (dynamic feed). The level in the aerator continues to increase; when the prefixed volume V_2 is reached, the feeding pump switches off and the fill phase ends. During the following phase (react), the biological reactions take place in the biofilter reactor, the effluent is continuously recirculated between the biofilter reactor and the aerator, and the aeration still operates in the aerator unit. When the biological reactions reach completion, the cycle continues with the draw phase. During this phase, both the air blowers and the recirculation pump are switched off and the effluent is progressively extracted from the aerator unit. Consequently, the liquid volume decreases progressively, until the value V_{RES} is reached. Then, a new operating cycle starts again following the same sequence as above described. When the head losses in the biofilter reactor reach an upper limit, a washing phase is added to the typical operating cycle, to remove both the detached biomass and the entrapped solids.

Figure 1 | Pilot-scale plant BIOSEQ in Casal Monastero.

Table 2 | Main geometrical characteristics of the BIOSEQ plant

Parameter	Value	Unit
Biofilter reactor		
Reactor diameter	1.0	m
Reactor height	2.4	m
Internal diameter	0.8	m
Working height	2.0	m
Working volume (V_B)	1.0	m^3
Aerator		
Internal diameter	1.5	m
Reactor height	2.4	m
Working height	2	m
Working volume (V_A)	3.5	m^3

Experimental phases

The experimental activity was performed through three phases: (1) inoculum formation, (2) start-up period and (3) regime conditions. During the first phase, the biofilter was filled with the effluent from the full-scale plant of Casal Monastero, whereas the aerator with the activated sludge from the biological reactor of the same plant. The sludge was recirculated between the two units under aerated conditions. The up-flow velocity in the biofilter was fixed to be about 2 m/h based on previous experiences. The start-up phase lasted about three months and aimed at developing the granular sludge by properly controlling the up-flow velocity which changed in the progression 2–2.5–3–3.2 m/h. Besides, the influent organic loading factor, F_{co}, was gradually increased, starting from 0.1 kg COD/m^3 d up to 0.9 kg COD/m^3 d (referring to the entire biofilter volume), by modifying either the number of daily cycles (from 1 to 2 and finally to 3 cycles/d) or the influent volume daily fed to the aerator (V_{feed}). During the regime conditions, the plant was operated at 3 daily cycles (each one of 8 h), a recirculation flowrate of 1.6 m^3/h and F_{co} in the range 0.3–0.9 kg COD/m^3 d. The washing phase was operated 1/week.

Analytical methods

Analytical determinations were carried out at least twice per week on representative samples of the influent and the effluent. The following parameters were measured by using the *Standard Methods for the Examination of Water and Wastewater* (APHA 1998): COD, filtrate COD (COD_F), Total Suspended Solids (TSS), total nitrogen (N_{tot}), NH_4^+-N, NO_2^--N, NO_3^--N. Besides, DO, pH and temperature values were continuously measured by using standard probes.

RESULTS AND DISCUSSION

Start-up period

Figure 2 shows the removal efficiency, E%, of COD and N_{tot} measured during the start-up period versus the number of daily cycles and the average influent organic loading factor (F_{co}). The removal efficiencies were calculated as follows: (COD_{IN} − COD_{OUT})/COD_{IN}, ($N_{tot\ IN}$ − $N_{tot\ OUT}$)/$N_{tot\ IN}$, where IN and OUT refer to the influent and the effluent, respectively.

It can be noted that the BIOSEQ plant performed very well since the beginning of the experimental activity, particularly for COD; besides, the efficiency remained high and quite stable despite the enhancement of the F_{co}. The removal efficiency was also always very high for TSS (not here shown), with an average value of 97%. The effluent concentrations of both COD and TSS remained far below the standards posed by law for the discharge into surface waters. About nitrogen removal, initially the nitrification process showed efficiencies above 99%, with nitrate concentrations in the effluent higher than law limits. After about two months, the number of daily cycles was increased to 3 and an anoxic phase was temporary added at the beginning of the react phase in order to favour the denitrification process. These variations were effectives and the nitrate concentration in the effluent decreased considerably; however, the nitrification was partly affected and nitrite rose appreciably. Nonetheless, the overall nitrogen removal efficiency continued to improve and the effluent characteristics complied with standards. Microbiological analyses on sludge samples collected from the reactor during this period demonstrated that the biomass was still predominantly in the form of activated sludge instead of granules; however, an abundance of filamentous bacteria

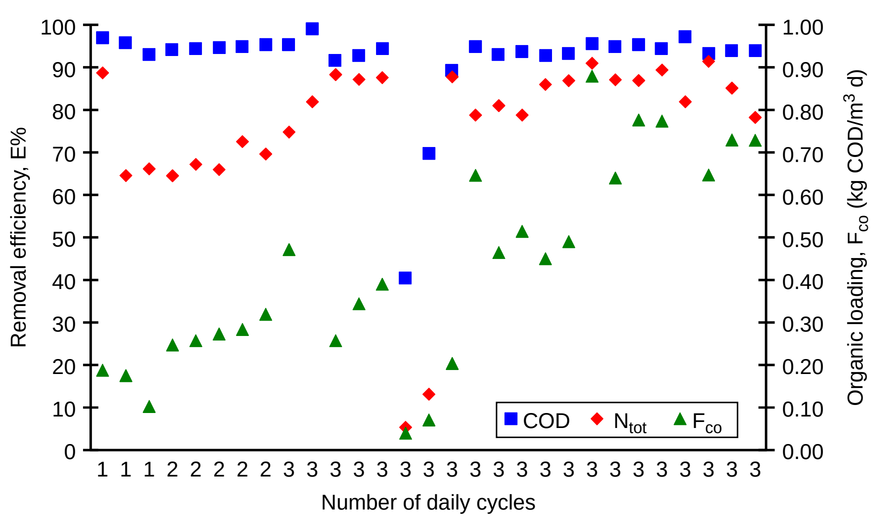

Figure 2 | COD and N_{tot} removal efficiency during start-up.

was observed, which are known to play an important role in granule development. Afterwards, the anoxic phase was eliminated while the F_{co} was still increased. Both the nitrification and also the overall nitrogen removal processes improved further, reaching efficiency of about 90%, with reduced concentrations of nitrates and negligible values of nitrites in the effluent. The better performances were attributed to the complete development of the granular sludge in the reactor, with the establishment of simultaneous nitrification–denitrification within the granules.

Regime conditions

In this phase, the removal efficiencies (E%) were related to the influent volume daily fed to the aerator, V_{feed}, since the number of daily cycles was maintained unchanged and equal to 3. Figure 3 shows the values of E% for COD and N_{tot} measured during the regime conditions versus V_{feed} and the average F_{co}. The COD and TSS removal efficiencies worsened, reaching average values of about 92 and 95%, respectively.

This performance decrease was attributed to the occurrence of peaks of COD in the influent along with some mechanical malfunctionings. Nonetheless, the effluent concentrations still remained far below the standards set by law for discharge into surface waters. The total nitrogen removal process was more affected by such problems and its efficiency dropped appreciably and in some cases the effluent concentration exceeded limits. Since both nitrates and nitrites remained low in the effluent, it was assumed that denitrification was still effective while nitrification did not function efficiently. Microbiological observations on sludge samples displayed destructured granules: this phenomenon was considered as a consequence of the operating problems and the cause of the reducing performance. In order to recover the granulation process, the F_{co} applied per cycle was reduced by decreasing the value of V_{feed} from 2.12 to 1.06 m^3. After a transition period, the system showed improved performances for all the parameters, and particularly for both N_{tot} and NH_4^+-N.

Comparison of BIOSEQ with the AS plant

A final comparison was carried out between the BIOSEQ pilot-plant and the full-scale continuous flow activated sludge plant of Casal Monastero based on their process efficiency, sludge production and energy consumption. The main technical advantages offered by the BIOSEQ plant and pointed out by the present experimental study can be summarized as follows:

- reduced footprint since both the biological reaction and the settle phase occurs in the same tank, as well as the nitrogen and the organic carbon removal;
- reduced environmental impact (odourless, low aesthetic effect, absence of sludge losses);
- absence of sludge settleability problems (such as bulking and foaming);

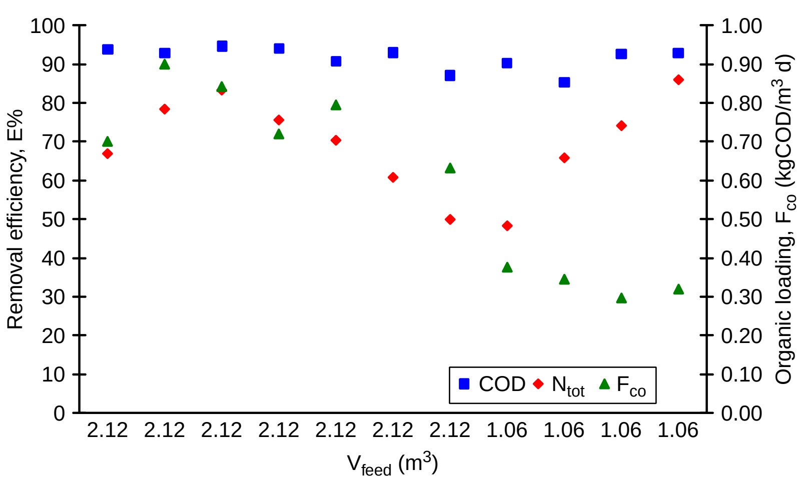

Figure 3 | COD and N_{tot} removal efficiency during regime conditions.

Table 3 | Average process efficiencies of the BIOSEQ and Casal Monastero plants

Average E%	BIOSEQ (start-up)	BIOSEQ (regime)	Casal Monastero (2008)
COD	91	92	86
TSS	97	90	86
N_{tot}	75	69	63
NH_4^+-N	93	71	77

- higher operative flexibility;
- chance to check effluent quality prior to discharging.

However, the BIOSEQ presents also several disadvantages:

- need of specialized manpower and advanced control instrumentations to promptly adopt corrective measurements when needed;
- sensitivity of the granulation process to influent variations and instable operating conditions;
- longer recovering periods after shocks;
- need of pre-treatment to remove solids (common to the AS plants).

About process performance in particular, Table 3 shows the average removal efficiencies in the start-up and regime periods measured in the BIOSEQ and Casal Monastero plants.

The BIOSEQ always showed better performances than Casal Monastero for COD and TSS treatment. The reduced nitrogen removal was attributed to the sensitivity of the nitrification process to the variations in the influent characteristics and the slow recovering of the granulation process.

These problems also prevented from testing the capacity of the BIOSEQ to treat higher influent organic loadings.

As far as the sludge production, P_x, is concerned, Table 4 shows data obtained for the BIOSEQ and Casal Monastero plants and from the specialized literature (Sirini 2002; Tchobanoglous *et al.* 2003).

Table 4 | Average sludge productions of the BIOSEQ and Casal Monastero plants

	P_x (kg TSS/kg $COD_{removed}$)
BIOSEQ	0.09
Casal Monastero	0.5
Literature	0.3–0.6

Table 5 | Comparison of the energy consumptions

	BIOSEQ	Castel Madama
Influent flowrate (m^3/d)	2.12	13
Equivalent inhabitants (EI)	10	65
Energy consumption (kWh/d)	18	26.44
Specific energy consumption (kWh/m^3)	8.5	2.0

The experimental activity confirmed that sludge production in the BIOSEQ plant is much lower than that of the AS plant. This result is attributed to the fact that endogenous conditions prevail within the granular biomass.

The comparison with the full-scale plant was carried out also based on the energy consumptions. The data for the BIOSEQ were measured during the regime conditions when the system worked through 3 daily cycles and treated a total wastewater volume of 2.12 m^3. The estimate took into account the following mechanical items:

- recirculation pump;
- feeding pump;
- blowers of the aeration system.

The results obtained were compared with the data of the smallest wastewater treatment plant managed by the Company Acea Ato2 S.p.A., which is located in Castel Madama (Rome). Table 5 shows the values in both cases, considering a daily water supply of 250 L/EI.

It can be noted that the BIOSEQ plant requires higher energy consumptions. This is mainly due to the operation of:

- the aeration system which must maintain DO concentration always proximal to saturation values in the aerator reactor;
- the recirculation pump since the influent flowrate to the recirculated flowrate ratio is much higher in the BIOSEQ: in the present case, the recirculation ratio was about 1:15.

CONCLUSIONS

The results obtained in the present study, despite related to a short period of operation, demonstrate that the BIOSEQ technology may show superior performance than a continuous flow activated sludge plant: for instance, it can achieve higher removal efficiencies in terms of COD, TSS and nitrogen removal, and a reduced sludge production. However, much concern needs to be paid in the start-up period to reach a complete development of the granular biomass. Besides, the energy requirements may lead to a cost rise.

More in general, it can be assessed that the BIOSEQ technology may be the optimal solution for the upgrading of existing plants or to serve new decentralized areas.

REFERENCES

APHA 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edition. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Arnz, P., Esterl, S., Nerger, C., Delgado, A. & Wilderer, P. A. 2000 Simultaneous loading and draining as a means to enhance efficacy of sequencing batch biofilm batch reactor. *Water Res.* **34**(5), 1763–1766.

Di Iaconi, C., Ramadori, R., Lopez, A. & Passino, R. 2005 Hydraulic shear stress calculation in a Sequencing batch biofilm reactor with granular biomass. *Environ. Sci. Technol.* **38**, 889–894.

Di Iaconi, C., Ramadori, R., Lopez, A. & Passino, R. 2007 Aerobic granular sludge systems: the new generation of wastewater treatment technologies. *Ind. Eng. Chem. Res.* **46**(21), 6661–6665.

Di Iaconi, C., De Sanctis, M., Rossetti, S. & Ramadori, R. 2008*a* Technological transfer to demonstrative scale of sequencing batch biofilter granular reactor (SBBGR) technology for municipal and industrial wastewater treatment. *Water Sci. Technol.* **58**(2), 367–372.

Di Iaconi, C., Del Moro, G., Lopez, A., De Sanctis, M. & Ramadori, R. 2008*b* Municipal wastewater treatment by a periodic biofilter with granular biomass. *Water Sci. Technol.* **58**(12), 2395–2401.

Dollerer, J. & Wilderer, P. A. 1996 Biological treatment of leachates from hazardous waste landfills using SBBR technology. *Water Sci. Technol.* **34**(7–8), 437–444.

Farabegoli, G., Chiavola, A. & Rolle, E. 2008 Remediation of chlorophenol- and phenol- contaminated groundwater by a sequencing batch biofilm reactor. *Water Sci. Technol.* **58**(2), 295–301.

Li, Y., Liu, Y. & Xu, H. 2008 Is sludge retention time a decisive factor for aerobic granulation in SBR? *Bioresour. Technol.* **99**(16), 7672–7677.

Liu, Y. Q. & Tay, J. H. 2006 Variable aeration in sequencing batch reactor with aerobic granular sludge. *J. Biotechnol.* **124**, 338–346.

Sirini, P. 2002 *Ingegneria Sanitaria-Ambientale. Principi, Teorie e Metodi di Rappresentazione*. McGraw-Hill, Milan, Italy.

Tchobanoglous, G., Burton, F. L. & Stensel, H. D. 2003 *Wastewater Engineering: Treatment and Reuse*. McGraw-Hill, New York, USA.

Wilderer, P. A. & McSwain, B. 2004 The SBR and its biofilm application potentials. *Water Sci. Technol.* **50**(10), 1–10.

Wilderer, P., Irvine, R. L. & Goronszy, M. C. 2001 *Sequencing Batch Reactor Technology*. Scientific and Technical Report no. 10. IWA Publishing, London, UK.