Simultaneous carbon and nitrogen removal from municipal wastewater in full-scale unaerated/aerated submerged filters

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Abstract

Characterization and evaluation of a biological submerged filter was carried out on a full scale pilot plant (design capacity = 200 inhabitants) performing removal of BOD and TN from pretreated urban wastewater. The submerged biofilter consisted of the 3 cells in series: one unaerated cell (predenitrification) and two aerated cells. Despite high variations in sewage composition, the pilot plant produced good discharge quality during steady-state operation. Average effluent BOD_5, COD and TN values were 11 mg/L, 58 mg/L and 15 mg/L. The reactor had been operating beyond its design capacity (up to 480 inhabitants), in spite of it, the results showed that this process can reach high BOD, COD and TN removal efficiencies: 97%, 94% and 75%, respectively. It indicates that this technology can absorb hydraulic and pollutant overloads while maintaining stable performance. Denitrification was performed by using sewage itself as carbon source. To improve the denitrification process, it was used an intermittent aeration cycle in the unaerated cell. The predenitrification with submerged unaerated filter has proved to be an efficient process for advanced removal of TN.

Keywords biofilm reactor, denitrification, nitrification, organic removal, submerged aerated filter, submerged unaerated filter.

INTRODUCTION

European standards are aimed to reduce total nitrogen (TN) discharge of wastewater treatment plants in so-called sensitive regions. The fixed-biofilm technology for urban wastewater treatment plant is an alternative to the activated sludge suspended growth process to biological removal of COD and TN. The submerged aerated filters (SAFs) are a biofilm technology that was commercially introduced in Europe from the middle of 1980. SAFs are biofilm systems in which a biofilm support medium is submerged in wastewater to create a large contact area for aerobic biological treatment. The biofilter can also be used in an unaerated mode (submerged unaerated filters – SUFs) as an anoxic stage for denitrification. Thus, these systems can be designed for carbon removal, nitrification and/or denitrification depending on process objectives (Schiegel and Koeser, 2007).

The SAF technology can be a cost-effective treatment solution for rural areas (Daude and Stephenson, 2003). SAFs are particularly suitable for small plants where robust, simple, compact treatment is desirable. Different from biological aerated filters (BAFs), the SAFs do not need backwash system to ensure the daily removal of excess biomass (Michelet *et al.*, 2005; de Barbadillo *et al.*, 2010). In recent years, several manufacturers have used SUF/SAF systems in small plants. Therefore, there is a need to thoroughly investigate and characterize full-scale SUF/SAF systems. Thus, in this report the operating with this technology for the treatment of municipal wastewater will be evaluated. The project was initiated in 2009 as an agreement with INNDES Ltd. to develop a submerged biological filter. In 2010 a full scale treatment system was built at the Abegondo (Spain) sewage treatment works served by a combined sewer system. The plant was designed for 200 population equivalents (200 PE), with 1 PE = 60 g BOD_5/day as Directive 91/271/EEC.

MATERIALS AND METHODS

The full-scale pilot plant was made of precast concrete, including 4 compartments arranged in series: predenitrification cell (SUF), organic aerobic oxidation cell (SAF-1), nitrification cell (SAF-2) and lamellar final clarifier (Fig. 1).

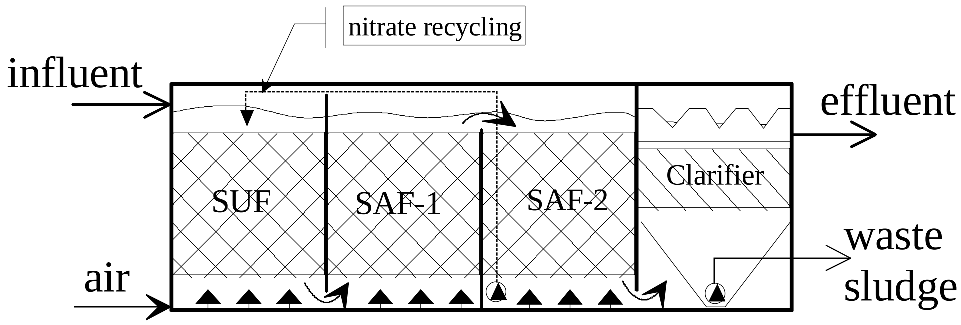

Figure 1 SUF/SAF system scheme

BIO-NET® grid structures made of polyethylene with a specific surface area of 150 m^2/m^3 were used in each cell for biofilm attachment. The surface areas of the support media available for biofilm growth were: 1012.5 m^2 (SUF); 1080 m^2 (SAF-1) and 1080 m^2 (SAF- 2). The empty-bed liquid volumes of each cell of reactor were: 11.7 m^3 (SUF); 10.42 m^3 (SAF-1) and 10.62 m^3 (SAF-2). Nitrate was recycled by pumping from the SAF-2 cell to SUF cell. All cells house a number of coarse bubble air diffusers. The aerators were situated 50 cm under the bottom of the modules BIO-NET. The SUF cell was operated with intermittent aeration cycle (on+off: 5+55 min).

The process was fed with pretreated urban wastewater. The composition of influent and clarified effluent was measured from 24-hours composite samples. The samples were analyzed for the following parameters: BOD_5 (OxiTop, WTW), COD, ammonium, nitrate, and total nitrogen (cuvette test - Dr. Lange and colorimetric analysis on a Lasa 50), pH, Alkalinity, nitrite and suspended solids (Standard Methods, 1998). In addition, dissolved oxygen (DO) and temperature were continually monitored and controlled with LDO™ probe and SC1000 controller (Lange, Berlin) in SUF cell. Occasionally, the concentrations of several parameters (e.g. COD, SS, nitrogen species, pH, DO) in the bulk liquid inside the 3 cells of reactor were measured from grab samples.

The influent volumetric flows, *Q*, ranged from 0.24 to 1.28 L/s (design *Q* = 0.4 L/s). Except for the first weeks after the startup of the reactor, the nitrate recycling flows, *R*, ranged from 2*Q* to 4*Q*. The hydraulic retention time (HRT) ranged of 7.6 to 30.3 hours based on total empty-bed liquid volume of reactor.

Volume and concentration of waste sludge were measured to estimate the sludge production in excess. To optimize the energetic demand, the aerobic cells were tested to intermittent aeration cycles (on+off). The cycles tested were: on-always, (30+30) min and (15+45) min. To measure the energy consumption due to the aeration a three-phase electrical meter was used (Chauvin Arnoux, model C.A 8332 B, France).

The pretreated sewage was used to seed the biological filter. The startup of the plant was made with a *Q* of 0.5 L/s and *R* of 5 L/s (R = 10 Q). During startup the organic loading was approximately 1 kg $BOD_5/m^3/d$. A higher *R* was used to minimize the growth of biomass in suspension. The startup period lasted three weeks.

RESULTS AND DISCUSSION

The operation was started in January 2010. The pilot plant has been extensively tested. The results at stable operation are summarized in Table 1. The reactor was exposed to variable weather conditions over a period of one year. During experimentation, the average water temperature in SUF cell ranged from 12 to 22 ºC. One of the experiences was the observation of biofilm accumulation on the support media. Distributed biofilm was to be found on the surface of the BIO-NET material a few days after the plant operation began (Fig. 2).

Table 1 Average influent and effluent concentrations and standard deviation (σ) of SUF/SAF process at steady state (24-hours composite samples, number of samples = 26)

Parameter	**Unit**	**Influent**	**Effluent**
BOD_5	mg/L	370 (250)	11 (7)
COD	mg/L	1015 (686)	58 (28)
TKN	mg/L	59 (40)	10 (7)
TN	mg/L	60 (39)	15 (6)
NO_x^--N[a]	mg/L	1.3 (1.2)	5.0 (3.0)
Alkalinity	mg/L as $CaCO_3$	162 (156)	75 (44)
pH		7.10 (0.21)	7.26 (0.21)

[a] NO_x^- - N = NO_3^- - N + NO_2^- - N

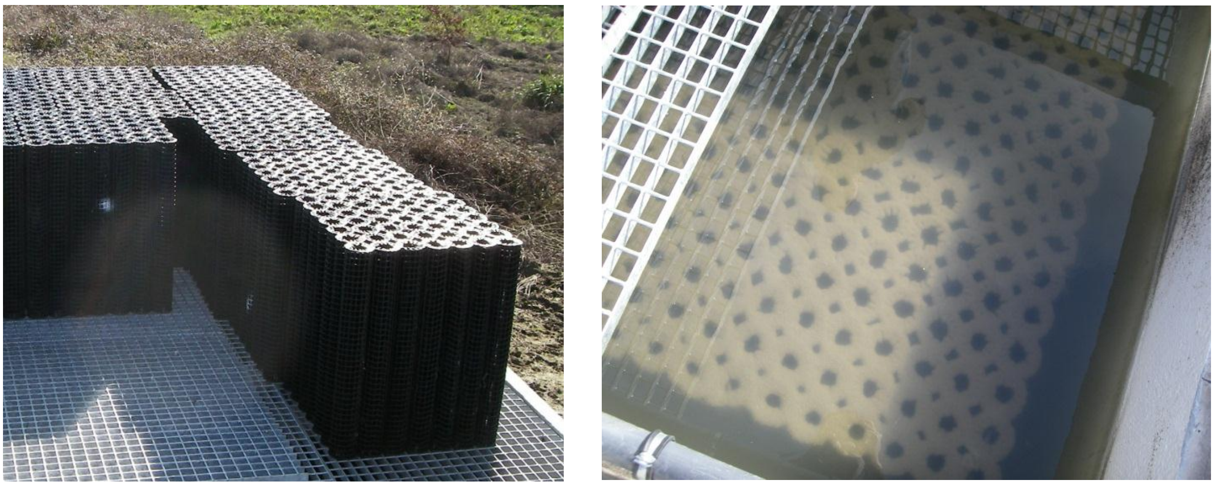

Figure 2 Structured packed rigid media (BIO-NET). Left: clear media. Right: biofilm developed on media after elapsed time 8 days of operation (SAF-1 cell)

Low influent concentrations were observed during prolonged rainfall. For example, influent COD concentrations ranged from 87 to 2650 mg/L while the corresponding BOD values varied between 60 and 1116 mg/L. However, the COD/BOD ratio obtained for the influent was 2.7, which indicated that the waste was biodegradable.

Organic removal

The performance process was evaluated in terms of the organic removal rates (r_O) expressed as kg COD (or kg BOD) /m^3/d. For a total bed volume of biofilter (21.15 m^3), the organic loadings (L_O) ranged from 0.2 to 3.7 kg COD/m^3/d (design L_O was 1 kg COD/m^3/d). For the overall range of L_O, COD average removal was 91 % (range: 66 – 98 %). r_O reached a maximum value of 3.6 kg COD/m^3/d. A lineal relationship was observed between L_O and r_O (as COD, Fig. 3) with a very high coefficient of determination (R^2) within the range of loading rates studied.

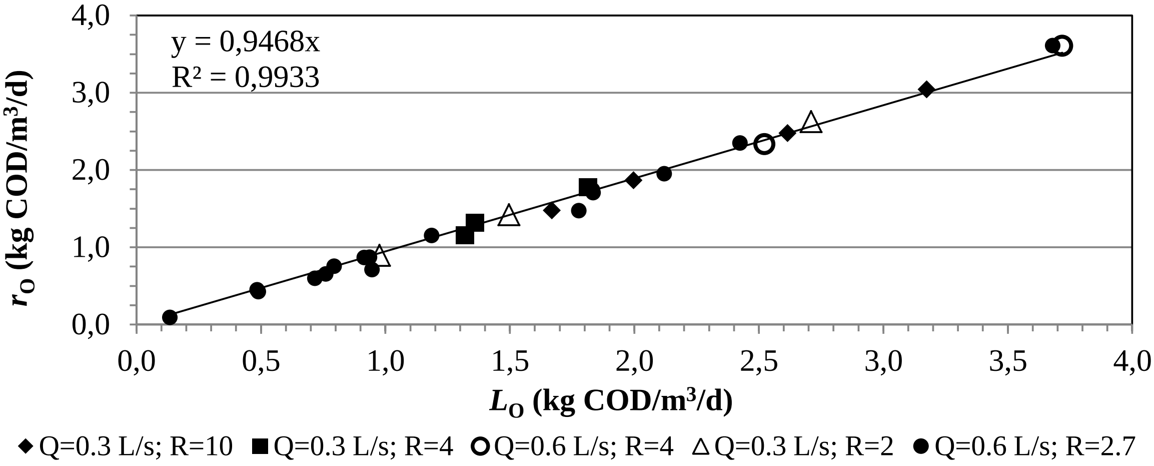

Figure 3 Effect of organic loading (as COD) on COD removal rate

Meanwhile, the BOD removal efficiency ranged from 87 to 99 % (average = 96±3 %). A high correlation was also observed between L_O and r_O (as BOD, Fig. 4). L_O ranged from 0.1 to 1.4 kg BOD/m^3/d (design L_O was 0.5 kg BOD/m^3/d) and r_O reached a maximum value of 1.3 kg BOD/m^3/d. The maximum loading rates beyond which the process may fail were not reached in the range of the values studied.

Effluent COD concentrations varied between 27 and 137 mg/L while the corresponding BOD values ranged from 4 to 32 mg/L. The effluent BOD and COD concentrations only were higher than 25 mg/L and 125 mg/L, respectively, in one sample. The effluent COD/BOD ratio ranged from 3.5 at high loadings to 11 at low loadings. It was variable depending on the process loading as also observed Hamoda and Al-Ghusain (1998).

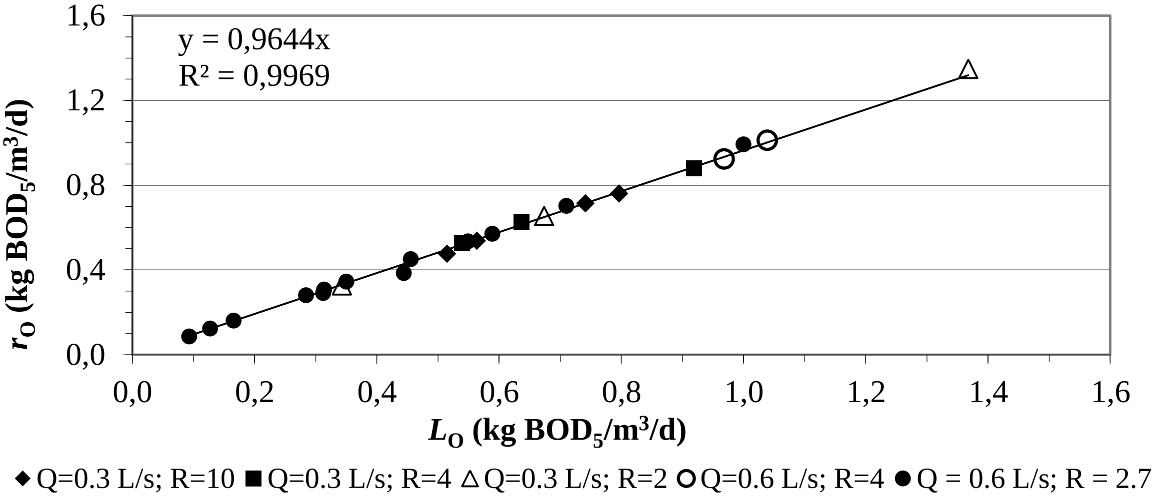

Figure 4 Effect of organic loading (as BOD) on BOD removal rate

Nitrogen removal

The TN removal took place by means nitrification – denitrification process. Predenitrification was performed by recycling nitrates back from the SAF-2 cell and by using sewage itself as carbon source. The TN load applied to SUF cell ($L_{TN,SUF}$) ranged from 0.04 to 0.67 kg TN/m^3/d (design $L_{TN,SUF}$ was 0.2 kg TN/m^3/d). The TN removal rate ($r_{TN,SUF}$) reached a maximum value of 0.55 kg TN/m^3/d. Also, a lineal relationship was observed between $L_{TN,SUF}$ and $r_{TN,SUF}$ (Fig. 5). For the overall range of $L_{TN,SUF}$, the global TN removal was 75 %, regardless of the nitrate recycling flow in the range of the values of *R* studied. The efficiency of denitrification decreased dramatically during rainy weather conditions. During days with normal weather conditions, the average TN removal was 71.6 %. Effluent TN concentrations varied between 8 and 31 mg/L. Five composite samples presented a value higher than 20 mg/L which is the daily average effluent quality requirement set by Directive 91/271/EEC for discharge of urban wastewater treatment plants in so-called sensitive regions of agglomerations between 10 000 and 100 000 PE.

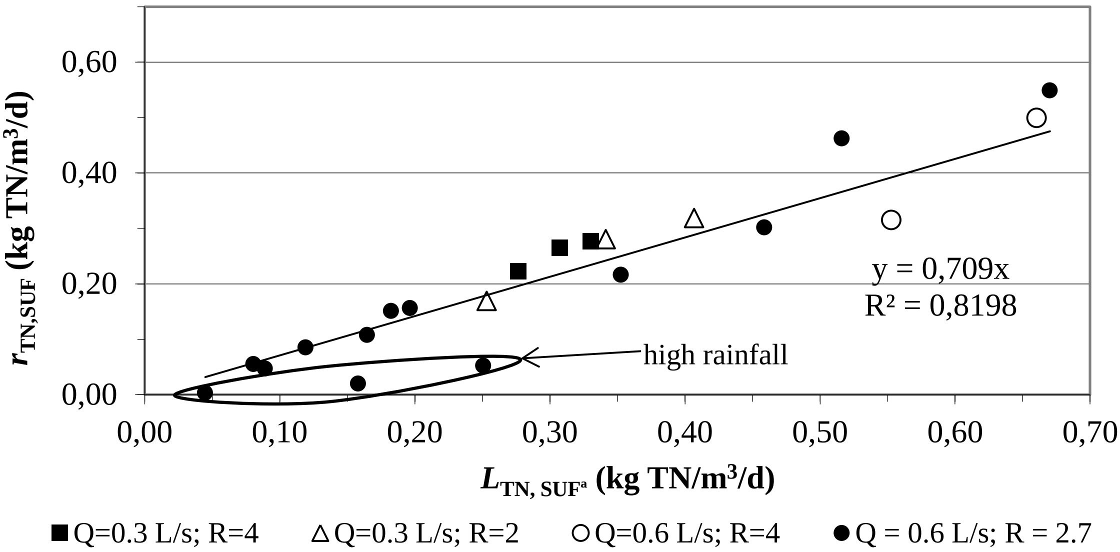

Figure 5 Effect of TN loading applied to SUF cell on TN removal rate in SUF cell

As did other researchers (Ryhiner *et al*., 1994; Canziani *et al*., 1999; Habermeyer and Sanchez, 2005), an intermittent aeration cycle was used in the SUF cell to improve the rate of diffusion of COD and nitrate into the biofilm. During aeration cycle the air velocity was approximately 6 m/h and the maximum DO concentration in bulk liquid reached 6 mg/L without inhibition of the denitrification process was taking place. Canziani *et al* (1999) also observed that denitrification occurred even at relatively high concentration of DO in the bulk liquid of submerged biofilter. Therefore, our SUF/SAF process achieved high organic and TN removal rates as long as the mass transfer limitations for nutrients were not reached.

The oxidized nitrogen effluent was in the form of nitrate, mainly. The effluent NO_3^- - N concentrations ranged from 0.01 to 8.7 mg/L (average value = 4.5 mg/L) while the corresponding NO_2^- - N values varied between 0.02 and 1.7 mg/L (average = 0.5 mg/L).

Monitoring of ammonium, nitrite and nitrate concentrations showed that nitrification was promoted in SAF-2 cell where BOD and COD concentrations were lower than SAF-1 cell. Furthermore, the pH values in SAF-2 cell were in the range of 6.3 to 7.5 in all the tests, which is considered an acceptable range for nitrification. Meanwhile the alkalinity values in the SAF-2 cell varied between 20 and 192 mg/L as $CaCO_3$ (average value = 61 mg/L as $CaCO_3$).

Process capacity

The full scale plant was made for a mass flux of 12 kg BOD_5/day (200 PE). The design considerations resulted in a total reactor volume of 0.16 m^3 per population equivalent. The plant was evaluated at different population equivalents. Fig. 6 displays the effect of PE on performance. It can be seen that the performance on BOD (or COD) was more stable than the corresponding TN values. At 200 PE the average removal achieved for BOD, COD and TN were: 97 %; 94 % and 75 %, respectively. It is remarkable that at 480 PE (one point) the COD removal was 97 % (98.6 % as BOD) while the corresponding TN value was 78 %. The capacity of the reactor, i.e. reactor size and bed area, is more effectively utilized at higher loading rates.

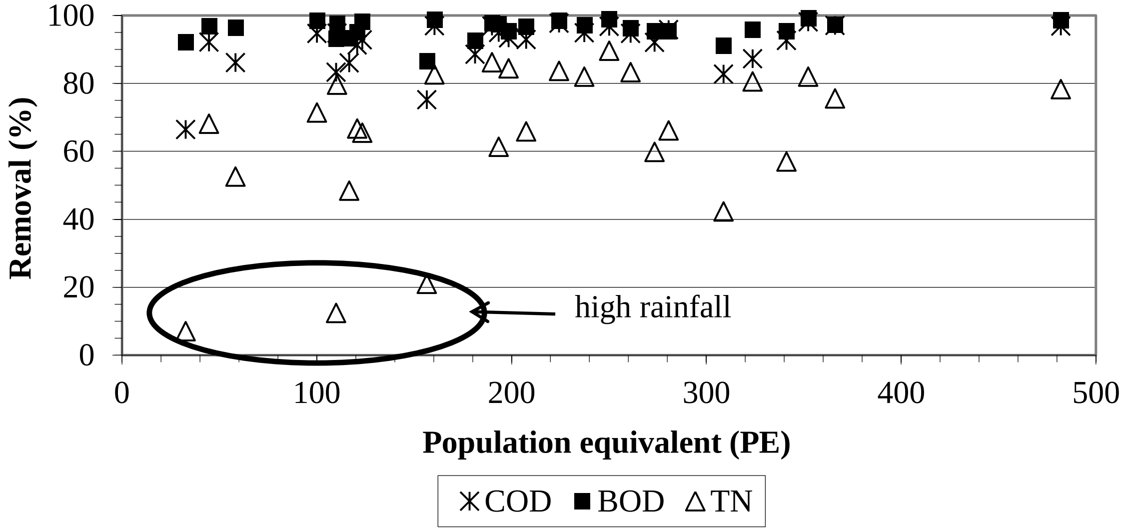

Figure 6 Effect of population equivalent on process performance

Energetic demand

The intermittent controlled aeration of aerobic cells, SAF-1 and SAF-2, resulted in high reduction of the specific energetic demand. The overall energy consumption reduction was between 50% and 75%. The results (table 2) correspond to cases with similar organic loadings.

Table 2 Specific energetic demand observed with optimizing of the aeration of aerobic cells (in kWh consumed/kg pollutant removed)

Aeration cycle (on + off)	**kWh/kg BOD_5**	**kWh/kg COD**	**kWh/kg TN**
on always	1.6	0.6	28.2
(30 + 30) min	1.1	0.4	8.9
(15 + 45) min	0.4	0.2	5.4

As shown in Table 3 during intermittent aeration cycles the average concentrations of clarified effluent in BOD_5/COD/TN were less than or equal to 25/125/15 mg/L.

Table 3 Operational results (average values) depending on aeration cycles

Aeration cycles →		**On always**		**(30+30) min**		**(15+45) min**	
Parameter	**Unit**	**In**	**Out**	**In**	**Out**	**In**	**Out**
BOD_5	mg/L	460	14	148	6	257	17
COD	mg/L	1330	69	382	32	610	75
TN	mg/L	78	17	23	10	31	15
t	days	209		45		60	

t = number of days of continuous assessment

Sludge characteristics

The waste sludge in excess ranged from 0.1 to 0.5 kg TSS/kg COD removed (average value = 0.3, from 14 measurements). A similar result has been observed by other researchers (Lessel, 1994; Fouad and Bhargava, 2005). The higher organic load increased sludge production. The concentration of waste sludge ranged from 2.5 to 5.6%, with an average volatile fraction of 0.62. Besides, the Sludge Volume Index (SVI) of the suspended solids in bulk liquid of SAF-2 cell (influent to clarifier) reached an average value ± standard deviation of 31 ± 13 mL/g (number of samples = 11).Thus, the sludge settleability was good. The SUF/SAF process didn't require backwashing because accumulated solids in the reactor were controlled by biomass sloughing and air-scouring. Without backwash system construction and operational costs are reduced, and generally permits the design of simple reactors with few working parts.

CONCLUSIONS

According to the results obtained in long-term research, the SUF/SAF process is simple and efficient for the treatment of urban wastewater from small agglomerations. The design of the full-scale plant demonstrated high overall removal efficiencies for BOD, COD and TN. In the range tested of BOD (or COD) and TN loadings the process worked with high stable performance. The pilot plant was designed to treat 200 PE (Q = 0.46 L/s). However, due to the high pollutant loading of the influent, the reactor effectively treated 250 PE for influent *Q* of 0.3 L/s, and 350 PE for *Q* = 0.6 L/s. This is a proof of the ability of this technology to absorb hydraulic and pollutant overloads while maintaining stable pollutant removal performance. The range of nitrate recycling flows from 2*Q* to 4*Q* can be applied for an efficient and economically predenitrification process. The intermittent controlled aeration of the SUF cell is adapted to obtain a high efficiency of denitrification process. Furthermore, the intermittent controlled aeration of aerobic cells resulted in high reduction of the specific energetic demand, but, it is needed to optimize the cycle of this aeration. The plant maintenance was simple and consisted mainly of the sludge removal from final clarifier. Finally, the good settleability of the biomass resulted in low concentrations of SS effluent.

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