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Influence of hydraulic residence time on the performances of an aerobic granular biomass based system for treating municipal wastewater at demonstrative scale

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ABSTRACT

The paper reports the results of an experimental investigation aimed at confirming at demonstrative scale the performances obtained, at laboratory scale, of an innovative aerobic granular biomass based periodic system (SBBGR) for treating municipal wastewater. A demonstrative SBBGR plant (i.e., a submerged biofilter that operates in a "fill and draw" mode) was built thanks to the financial support of the EU Life programme (PERBIOF project). The results show that after the generation of granular biomass during the start-up period, the SBBGR system was able to remove 80–90% of COD, total suspended solids and TKN in primary effluent from a municipal wastewater treatment plant, independently of the hydraulic residence time investigated (i.e., from 12 down to 3 h). The process was characterised by a very high sludge age value ($\theta c \approx 150$ d) that led to a biomass concentration as high as 35–40 g TSS/L_{bed} and a sludge production much lower than that commonly reported for conventional treatment plants.

Keywords: Aerobic granulation at demonstrative scale; SBBGR system; Municipal wastewater treatment; Sludge production

1. Introduction

Some of the major problems in the field of biological wastewater treatments are due to the difficulty of treating diluted wastewater (e.g., municipal wastewaters) because of the low biomass concentration achieved in conventional treatment plants such as activated sludge systems. These systems are featured by poor conversion capacities, large area requirement (high footprint) and high production of surplus biomass [1]. Presently, a lot of efforts are in progress worldwide to find effective alternatives to conventional technologies (i.e., innovative systems with greater compactness, better operational flexibility and lower sludge production) [2,3].

In such a contest, the Water Research Institute (IRSA) of the Italian National Research Council (CNR) during

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the last years is involved in developing a new technology, whose acronym is SBBGR (Sequencing Batch Biofilter Granular Reactor). Such a technology is based on a submerged biofilter that operates in a "fill and draw" mode, and is featured by maximum efficiency and minimum sludge production.

The high effectiveness of SBBGR is due to the peculiar characteristics of the biomass growing into the reactor. In fact, under specific operational conditions [4], the biomass grows as granules characterized by a very high density, up to 4–5 times higher than that recorded for biomass growing in conventional suspended biomass systems. The granules are entrapped in the pores produced by packing the filling material allowing greater biomass retention in the reactor to be obtained (up to 40 g TSS/L_{bed}) with interesting repercussions on substrate conversion capacities and sludge production.

In SBBGR system, the granulation process takes place during the reactor start up period. Four steps can be distinguished in this process: 1) the formation of a thin biofilm that completely covers the carrier surface; 2) the increase of biofilm thickness; 3) the break-up of attached biofilm with the release of biofilm particles; 4) the rearrangement of biofilm particles in smooth granules [5]. In previous investigations, the authors found that three factors play a decisive role in granular biomass generation: hydrodynamic shear forces; start-up operative conditions (i.e. the pattern of organic loading rate increase); and bed material features [5,6].

IRSA has developed and successfully applied such a technology for treating, at laboratory scale, municipal and industrial wastewater [7–9]. More recently, a demonstrative unit was built up thanks to a grant of the European Commission (PERBIOF project; LIFE05 ENV/IT/000868; www.perbiof-europe.com). Therefore, with the cooperation of IRIDE SpA (one of the biggest Italian multi-utilities companies) and Université de Savoie, France a demonstrative plant was designed and constructed. This plant was fed with the primary effluent coming from the municipal WWTP (200,000 i.e.) of Bari West, a town located in Apulia, a Southern Italy Region. The present paper reports the results obtained during this experimental campaign.

2. Materials and methods

2.1. Demonstrative SBBGR system and operation

The SBBGR prototype used during the present experimentation consists of a cylindrical zinc plated steel reactor having a diameter and a height of 1 and 3 m, respectively.

In Fig. 1 that shows a sketch and photo of the prototype it is possible to observe that the SBBGR consists of 3 main parts laid one upon the other:

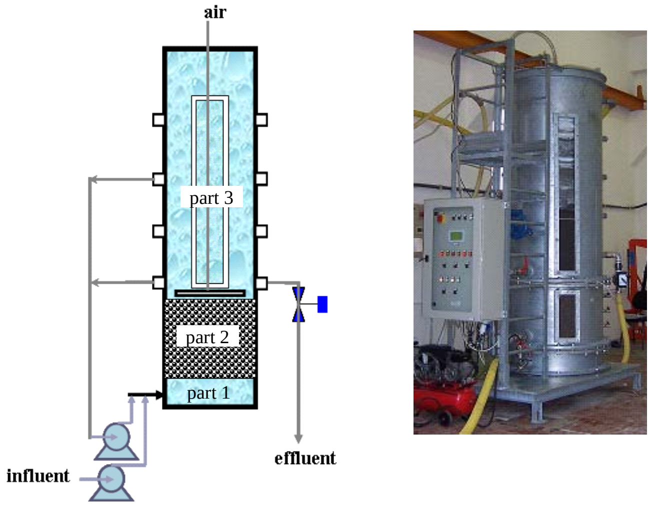

Fig. 1. Sketch and photo of SBBGR.

- The lower part (part 1; height: 30 cm) distributes to part 2 the influent fed by volumetric pump and/or semi-treated wastewater taken from part 3 by a recirculation pump;
- The central part (part 2; height: 70 cm) is the reactive one as contains the biomass. This part is filled with biomass support material (KMT-k1 wheel shaped plastic elements from Kaldness; length: 7 mm, diameter: 10 mm, specific surface: 630 m^2/m^3, density: 0.95 g/cm^3, bed porosity: 0.75). Such a material is confined between two surfaces of slabs with 18 diffusers in order to obtain a good distribution of the liquid and air in the biomass zone. A window-type opening is provided on the upper surface for allowing biomass sampling for the analysis;
- The higher part (part 3; height: 2 m) basically is a storage tank where aeration takes place. A volumetric pump recirculates (flow rate: 2 m^3/h) the oxygenated liquid from part 3 to part 1. The pump can extract the liquid at two different levels as shown in Fig. 1. The aeration is performed by a blower connected with some diffusers (fine bubble disc system).

The SBBGR carries out a treatment cycle consisting of three consecutive phases: filling, reaction (under aerobic conditions) and drawing. In the filling phase, the wastewater to be treated is fed into part 1 of the reactor. During this phase, the liquid passes through the bed (i.e. part 2) and then goes to part 3. When a first, predetermined, liquid level in part 3 is reached, the recirculation pump and blower start. Under these conditions, the aerated wastewater reaches part 1, passes through the bed (i.e., part 2) together with raw wastewater and then reaches part 3 where it is aerated and recycled again. When a second, predetermined, liquid level in part 3 is reached, the filling pump stops while the liquid recirculation continues until the end of the reaction phase. Finally, the treated wastewater is drawn out by a motorised valve located at the bottom of part 3 (Fig. 1).

The operative schedule (filling, recirculation, aeration, drawing, etc.) is completely automated by a programmable logic controller (PLC) although the plant components can also be switched on or off manually. A pressure meter set at the bottom of the reactor (part 1) measures on-line biofilter head losses due to biomass growth and retained suspended solids occurring in the wastewater during reactor operation. When a fixed value of head loss is reached (i.e., 300 cm), a washing step is carried out by compressed air until the headloss decreases to a definite value (i.e., 100 cm). Washing water was collected and measured (as TSS) in order to calculate the specific sludge production. During the experimental period, the air and liquid recirculation flow rates, 3 and 2 m^3/h, respectively, were controlled by flow meters whereas the pH value, continuously monitored, was always in the range 7.0–8.0.

The SBBGR system was set up at a large municipal wastewater treatment plant (200,000 p.e.), located in Southern Italy (Bari) and activated sludge from the plant was used as inoculum.

During the 3 month start-up period (period A), particular attention was paid to the generation of granular biomass. Specifically, taking into account the wastewater composition, the organic loading value was progressively increased from 0.05 up to 0.5 $kg_{COD}/m^3 \times d$ by adjusting the wastewater volume fed to plant. Once granulation had been achieved, the experimental activities continued in order to assess both granule stability and plant performances. In particular, during this period (period B) the hydraulic residence time was progressively decreased from 12 to 3 h by increasing the daily number of treatment cycles.

2.2. Wastewater composition

SBBGR was fed with the primary effluent coming from the municipal wastewater treatment plant of Bari West whose composition is reported in Table 1.

Table 1
Composition range of municipal wastewater fed to SBBGR during the investigation period

Parameter	Value range
COD, mg/L	200–500
COD_{sol}, mg/L	150–280
TKN, mg/L	35–60
NH_4-N, mg/L	25–45
NO_3-N, mg/L	0–2
pH	7.2–7.6
Chlorides, mg/L	600–1,500
PO_4-P, mg/L	2–3.5
TSS, mg/L	70–160
VSS, mg/L	60–140

2.3. Analytical methods

COD (chemical oxygen demand), TKN (total Kjeldahl nitrogen), TSS (total suspended solids) and VSS (volatile suspended solids) were determined according to standard methods [10]. DO (dissolved oxygen) and pH were measured on-line by using selective probes whereas ammonia and oxidised nitrogen were measured by on line analyzer UV 400 Tethys. In particular, oxidised nitrogen was measured by UV light absorption at 210–220 nm in a flow cell; turbidity, organic matter, suspended solid or dirty in the flow cell were automatically compensated by a differential measurement with a second detector at a reference wavelength. As for ammonia, the instrument uses a method known since 1956 (Gunther) but that requires a strong mathematical signal processing that only powerful-microprocessor based instrument can handle. The measuring principle is based on UV light absorption spectrum of ammonia gas produced by adding a small amount of sodium hydroxide to the sample and its successive purging. A Fast Fourier Transform (FFT) is then applied on the spectrum to extract the absorption signal typical to ammonia gas. The method is very selective and does not suffer any interference; moreover, considering that the measurement is performed in the gaseous phase, the analysis is not influenced by turbidity or colour.

Biomass concentration was evaluated in terms of dry weight on a representative bed volume (as g TSS/L_{bed}). In particular, a bed volume was withdrawn from the reactor by a particular ladle and suspended in tap water. When suspended in water, the biomass granules spontaneously parted from the carrier and, after collection, measured as TSS. The biomass attached to carrier elements was completely detached by shaking with glass rod many times and also measured as TSS. The sampled bed volume was determined by counting the carrier elements and relating them to carrier element number in 1 L of bed (i.e., 1023).

The specific sludge production was calculated assuming that SBBGR operating conditions, in particular the very high sludge age, guaranteed the complete metabolization of all particulate organic matter occurring in the wastewater. Accordingly, the specific sludge production (kg TSS/ kg $COD_{removed}$) was calculated dividing TSS removed during the washing operation) by the amount of COD removed during the interval between two washing operations.

Instantaneous and composite samples of influent and effluent were taken using automatic samplers.

3. Results and discussion

Biomass granulation was obtained close to the end of the start-up period. Throughout this period, the hydraulic loading was adjusted in order to obtain a progressive increase of organic loading from a minimum of 0.05 $kg_{COD}/m^3 \cdot d$ up to a maximum value of 0.5 $kg_{COD}/m^3 \cdot d$. In particular, during the first few days of the start up period, it was observed that a thin biofilm completely covered the carrier surface. Later on, an increase in biofilm thickness was recorded that led to an increase in both biomass concentration and headloss values. Subsequently, detachment of biomass particles was observed with deposition inside the interstitial pores of the carrier (i.e., the pores produced by packing). The particles entrapped inside the carrier still continued to grow reaching size and shape similar to granules. At the end of the start-up period, the headloss along the whole bed and the average biomass concentration were 3 m and 35 g TSS/L_{bed}, respectively. The granules were the prevailing form of biomass present in the bed. In fact, specific quantitative measurements (see material and methods section) showed that about 75% of biomass content in the bed was made of granules. Looking at Fig. 2, which shows a photo of biomass granules, it is possible to see that the maximum diameter of the granules was 4–5 mm.

After the start-up period, the plant was operated for several months during which the hydraulic residence time of the SBBGR was progressively decreased from 12 to 3 h by increasing hydraulic loading (i.e., by increasing the number of treatment cycles per day). Referring to this period (period B), Fig. 3 shows COD and TSS average concentrations recorded in the SBBGR effluent as well as their relative removal efficiencies all as functions of hydraulic residence time.

Fig. 3 shows that the COD concentration in the effluent was always lower than 60 mg/L with removal efficiencies higher than 85% independently of hydraulic residence time and influent COD value. Such a result can be ascribed to the great operation flexibility and stability of the SBBGR system towards volumetric flow rate and wastewater composition changes.

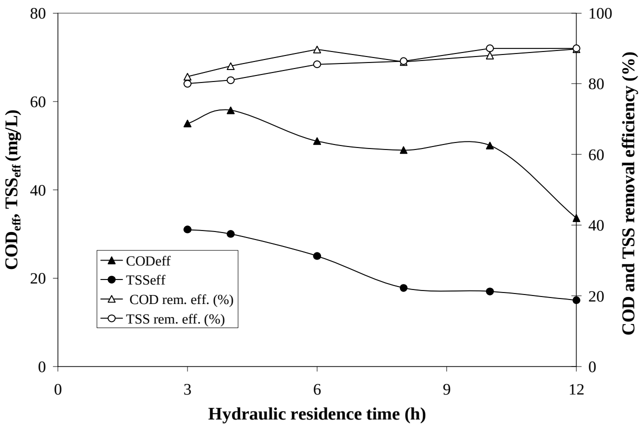

Fig. 3. COD and TSS concentrations in the effluent and their relative removal efficiencies as functions of hydraulic residence time during period B.

Fig. 2. A picture of the granules.

Regarding TSS, the data in Fig. 3 show that the concentration of total suspended solids in treated effluent was lower than 25 mg/L with removal efficiencies higher than 80% once again independently of the hydraulic residence time value and influent TSS value. Such good filtration performances can be ascribed to the low bed porosity values reached (i.e. lower than 0.15).

As for nitrogen, Fig. 4 reports, for the same period, TKN and oxidised nitrogen average concentrations recorded in the effluent as well as TKN removal efficiency all as functions of hydraulic residence time.

Looking at Fig. 4, it is possible to observe that the removal of TKN was always higher than 80% even when the minimum hydraulic residence time was applied (i.e., 3 h). Moreover, oxidised nitrogen (NO_x-N) concentration in the treated effluents was always lower than 5 mg/L. Considering that in the treatment cycle no anoxic phase was planned, such a result indicates that in the reactor simultaneous denitrification occurred. This result can be ascribed to both high biomass concentration (around 40 g TSS/L_{bed}) and transient conditions. In such conditions, in fact, oxygen cannot penetrate inside the deeper layers of biomass and denitrifying bacteria can find carbon sources coming from storage or hydrolysis products of particulate organic matter present in the feed.

Referring to sludge production, Fig. 5 shows the profile of headloss across the bed (i.e., part 2 of prototype, Fig. 1) measured between the interval of two washing operations in period B.

Looking at this profile, it is possible to observe that headloss ranged from a minimum value of 100 cm (i.e.,

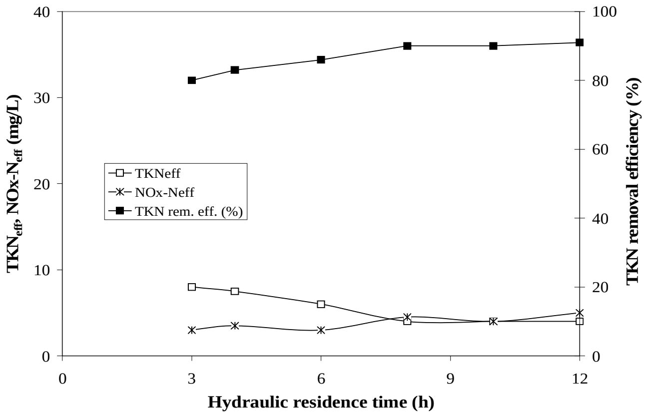

Fig. 4. TKN and NO_x-N concentrations in the effluent and TKN removal efficiencies as functions of hydraulic residence time during period B.

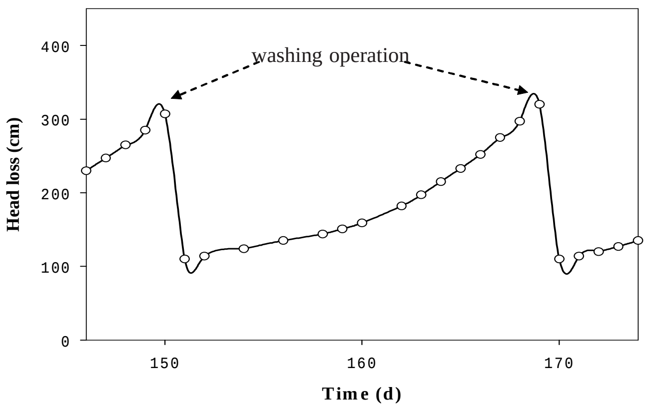

Fig. 5. Head loss profile recorded in period B during the interval between two washing operations.

the value just after the washing operation) to a maximum value of 300 cm (i.e., the value set for carrying out the washing operation). The headloss increase recorded in the prototype bed was however slower than that recorded in continuous conventional biofilters [11], where washing operations are usually carried out every 1–2 days causing an excess sludge production as high as 0.5–0.6 kg TSS/kg $COD_{removed}$ [12,13]. On the contrary, as shown in Fig. 5, in the SBBGR prototype, the washing operations were carried out every 10–15 days and a sludge production value of 0.1 kg TSS/kg $COD_{removed}$ was obtained. This low value of sludge production can be ascribed to the very high sludge age value (θc ≈ 150 d) of SBBGR that led to a biomass concentration as high as 35–40 g TSS/L_{bed}

4. Conclusions

The main results obtained during an investigation aimed at evaluating the effectiveness of an aerobic granular biomass based SBBGR system for treating municipal wastewater have been the following:

- Granular biomass generation was obtained during the first 90 days of the experimental period;
- The SBBGR performances were characterised by satisfactory COD, nitrogen and total suspended solids removal efficiencies (all higher than 80%) throughout the whole experimental period. In addition, such high removals were almost independent of investigated hydraulic residence time (i.e., from 12 down to 3 h);
- The process was characterised by a very low sludge production (i.e., 5–6 times lower than that commonly reported for conventional systems).

The prototype is currently being used, for the treatment of tannery wastewater, chosen as representative of industrial wastewater. Considering the presence in such industrial wastewater of a relevant fraction of recalcitrant organics, the biological treatment is being integrated with a chemical oxidation, performed by ozone, aimed at rendering biodegradable the refractory compounds.

Detailed information about the activities carried out and the results achieved in PERBIOF project are reported at www.perbiof-europe.com.

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