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Upgrading small wastewater treatment plants with the sequencing batch biofilter granular reactor technology: Techno-economic and environmental assessment

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ABSTRACT

This paper is aimed at evaluating, from a techno-economic and environmental point of view, the performance of an existing wastewater treatment plant in which the traditional biological section is upgraded with an innovative Sequencing Batch Biofilter Granular Reactor. Two scenarios were simulated in order to model and assess the performances of conventional (CAS, Conventional Activated Sludge) and innovative solutions, based on mass balances, techno-economic evaluation and environmental assessment. The results showed that converting the activated sludge process into an SBBGR allows to achieve a drastic reduction in sludge production (up to 75% as volatile suspended solids). Furthermore, the secondary sedimentation and sludge stabilization units can be dismissed, reducing the area requirement (up to 50%). The technical assessment is mainly positive, with the electric energy consumption being the only critical item. The higher energy demand of the upgraded plant (about 25% more than the conventional treatment) is mainly associated with the recycle flow in the SBBGR system. Although the economic sustainability of the upgraded plant depends on local conditions, it can be considered to be likely favourable: sludge disposal and materials & reagents costs, together with the investment for plant reconstruction are those items that should be carefully evaluated before upgrading the CAS plant with SBBGR technology. The environmental assessment shows also mostly positive results, although it points to the increased phosphorus concentration in the effluent as a potentially critical issue and it highlights the electricity use and the increased nitrous oxide generation as other matters that need to be carefully checked in real case application.

1. Introduction

The management of sludge produced during municipal wastewater treatment is an issue of increasing importance. Although the volume of sludge produced is only about 2% of the treated wastewater volume, its treatment and final disposal entails very high capital and operating costs to 50% of the total operating costs of the wastewater treatment plant (Horan, 1990; Wei et al., 2003; Pérez-Elvira et al., 2006; Ozdemir and Yenigun, 2013).

Sludge amounts have dramatically increased worldwide over the last two decades. In Europe (EU-15), an increase of about 50% was observed from 1998 to 2005, reaching an annual production of 9.8 million tons dry solids (Foladori et al., 2010). Including also the contribution from EU-12 countries (i.e., the new Members States that joined EU after 2004) a global value close to 11 million tons dry solids can be obtained (Kelessidis and Stasinakis, 2012). These figures are expected to increase further, as a result of both more stringent effluent regulation and a growing number of wastewater treatment plants. In response to this increased sludge production and to concerns related to efficient management of resources, various approaches are often considered for plants upgrading and

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refurbishment for recovery of material and energy from sludge, including sludge quality control to allow for agricultural use (Wang et al., 2008). However, these options are usually not feasible or convenient in case of small treatment plants (due to low sludge quality and/or amount) or high industrial contributions (resulting in poor sludge quality). In these cases, reducing the excess sludge production appears to be the only possible way to minimize treatment, transport and disposal costs.

In the last decade, a new biological system, the Sequencing Batch Biofilter Granular Reactor (SBBGR), has been developed and tested for municipal and industrial wastewater treatment. This system is able to significantly reduce the quantity of sludge in comparison with the biological stage of a conventional wastewater treatment plant (Di Iaconi et al., 2010a). SBBGR consists of a single basin operated in cycles of wastewater feeding, treatment and discharge. It combines the advantages of attached biomass systems (i.e., robustness and compactness) with those of periodic systems (i.e., flexibility and stability) (Rodgers and Zhan, 2003; Bajaj et al., 2008; Farhadian et al., 2008). Similarly to these systems, SBBGR presents a higher potential for use than suspended growth biomass reactors since it can retain a higher concentration of biomass with higher metabolic activity. Moreover, the attached biomass is usually found to be more resistant to toxicity (Pedersen and Arvin, 1995), and so better suited for the treatment of industrial effluents. SBBGR is, however, a unique system in virtue of the particular type of biomass growing in it, which consists of two different fractions: the biofilm attached to the carrier material and the biomass granules entrapped in the pores produced by packing a part of the reactor with a filling material (Di Iaconi et al., 2010a). It is worth noting that in SBBGR, the granules are retained by the filling material rather than being suspended as in recently proposed granular biomass sequencing batch reactors (Gao et al., 2011; Pronk et al., 2015). The whole biomass (i.e., biofilm and granules) is completely confined in a dedicated zone of the reactor known as the bed (or biofilter), and a secondary settler is therefore no longer necessary. This feature gives a great advantage in terms of operating stability compared to granular biomass sequencing batch reactors, where selection of granular biomass and washing out of floccular biomass are obtained by applying a very short sedimentation phase (Qin et al., 2004). Such a hydraulic selective pressure may also lead to the washout of the granular biomass from the reactor when slight modifications of the granule structure and density occur (e.g., in the case of filamentous bacteria growth). In fact, the long-term instability of granular biomass is one of the major bottlenecks that have prevented the practical full scale application of the innovative aerobic granular sludge technology (Lee et al., 2010). This drawback cannot occur in a SBBGR system since there is no sedimentation phase as the biomass is entrapped in the filling material. This efficient biomass retention allows to achieve very high sludge age in SBBGRs (up to one order of magnitude higher than in conventional suspended growth systems), with consequent reduction of sludge production (Di Iaconi et al., 2009). In fact, the microorganisms spend much time in the endogenous metabolism phase, where the contribution of biomass decay rate on biomass growth rate becomes relevant (Di Iaconi et al., 2010a). Moreover, due to both high biomass concentration and dynamic conditions arising from the sequential operation, the SBBGR biomass is exposed to the alternation of aerobic and anaerobic conditions that activates an uncoupled metabolism (Liu, 2003). Thus, dissipating catabolically extracted energy limits anabolism and results in a reduced biomass yield (Low et al., 2000), as observed in other systems with alternating exposure to oxic and anaerobic environments (Wei et al., 2003). This has been clearly demonstrated for SBBGR, when this replaced the activated sludge stage of a conventional wastewater treatment plant (based on primary and secondary treatment) and a significant reduction of sludge production was obtained (Di Iaconi et al., 2010a).

The SBBGR technology has been successfully applied for treating various types of wastewater (municipal wastewater, landfill leachates, tannery and textile effluents). In particular, in the case of primary municipal effluents, the SBBGR removed 80% of chemical oxygen demand (COD), total suspended solids (TSS) and nitrogen content, ensuring residual concentrations lower than the Italian limits for discharge into soil. These performances were assured up to organic loading rate (OLR) as high as 2.5 kg COD/m^{3}d (Di Iaconi et al., 2010a). In the treatment of scarcely biodegradable tannery wastewater, with biochemical oxygen demand (BOD_5) to COD ratios of 0.41–0.43, removal efficiencies of 91%, 90% and 78% were obtained for COD, TSS and ammonia, respectively, when operating the SBBGR at OLR of 2.1 kg COD/m^{3}d (Di Iaconi et al., 2010b). Also in the case of mature municipal landfill leachates characterized by high values of ammonia concentration (1.5–2 gN/L) and salinity (16–22 mS/cm), the SBBGR technology was able to produce an effluent with concentrations of ammonia and oxidised nitrogen as low as 10 and 20 mg/L, respectively (Di Iaconi et al., 2011). Finally, during the treatment of mixed municipal and textile wastewater, the SBBGR reached removal efficiencies of 82%, 95%, 88% and 77% for COD, TSS, total Kjeldahl nitrogen (TKN) and surfactants, respectively, allowing to meet the Italian limits for discharge into surface water with no need of further tertiary treatment and with much lower hydraulic residence time (11 h against 30 h) than in the centralized plant treating the same wastewater (Lotito et al., 2014). For all wastewater types, SBBGR was characterized by a low specific sludge production (0.12–0.14 $kg_{TSS}/kg_{CODremoved}$) due to the high biomass age of SBBGR system (higher than 200 d).

So far, the applicability and sustainability of SBBGR at full scale have not been demonstrated. Therefore, the aim of this study was to simulate the application of this technology for the upgrading of a conventional activated sludge (CAS) treatment plant, equipped with aerobic sludge stabilization and having a treatment capacity of 15,000 person equivalents (PE). The two configurations were compared based on the results of mass and energy balances and a techno-economic and environmental assessment of full-scale designs. Plant-wide mass and energy balances were performed on the basis of literature data (for CAS) and experimental results deriving from a pilot plant monitoring campaign (for SBBGR). The results of these balances were used for a techno-economic and environmental assessment of the conventional and upgraded configurations.

2. Materials and methods

2.1. Pilot experiments

The effectiveness of the proposed upgrading scheme was evaluated by experiments on a demonstrative scale SBBGR prototype (a pilot plant having a volume of 300 L). A detailed description of the prototype configuration and operation is reported elsewhere (Di Iaconi et al., 2014). The main feature of the prototype was the complete separation of the biomass from the liquid phase. While the biomass was confined to a dedicated compartment of the reactor (biofilter) packed with plastic material (wheel shaped elements), the wastewater was circulated between an aeration compartment with continuous air supply and the biofilter where the biological degradation processes occurred. By this way, the treated wastewater was always free of biomass and could be easily disposed of. A sketch of SBBGR is shown in Fig. 1.

The operation of the prototype was based on a succession of 6-h treatment cycles, each consisting of three consecutive phases: filling, reaction and drawing. During the filling phase a fixed