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Review

Sequential anaerobic–aerobic treatment for domestic wastewater – A review

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ABSTRACT

Introduction, consolidation and even standardization of expensive conventional aerobic systems for domestic wastewater treatment imposed significant financial constraints on the expansion of sanitary services including treatment in developing countries. A viable alternative is the sequential anaerobic–aerobic systems. If compared with the conventional aerobic technologies based on activated sludge processes, lower energy consumption and lower excess sludge production can be achieved with a high-rate anaerobic pre-treatment step. Particularly with concentrated sewage, the energy benefit of applying anaerobic pre-treatment will become very significant. This study aims on putting the effectiveness of sequential systems for treatment of domestic wastewater on view, through displaying results presented in literature on the performance of these systems.

1. Introduction

Conventional aerobic technologies based on activated sludge processes are dominantly applied for the treatment of domestic wastewater due to the high efficiency achieved, the possibility for nutrient removal and the high operational flexibility (Gavrilescu and Macoveanu, 1999). Nevertheless, the high capital and operational costs that coincide with the introduction of these technologies impose significant financial constraints on expanding the sewage treatment coverage, particularly in the low income countries. Therefore, to smooth the progress of sanitation services including conveyance and treatment, reliable, unsophisticated and cost-effective treatment technologies should be adopted. Moreover, in countries of limited water resources like Jordan, treated wastewater is accounted for in the national water budget for mainly agriculture usage. Hence, extending sanitation services would result in the development of new urban wastewater ‘reuse’ schemes. Subsequently, agricultural use of treated sewage will stimulate the (peri)urban food production and will reduce the amounts of fresh water allocated to agriculture.

Anaerobic (pre-)treatment of domestic wastewater can serve a viable and cost-effective alternative (Lettinga, 1995) due to its relatively low construction and operational cost, operational simplicity, low production of excess sludge, production of energy in form of biogas and applicability in small and large scales. Moreover, owing to its compactness it can be located near or even inside the area of wastewater collection, stimulating (peri-) urban reuse. Since anaerobic treatment is a pre-treatment method, an adequate post treatment system is required to reach to local standards for discharge and/or agricultural reuse (Elmitwalli et al., 2003; Tawfik et al., 2005; Chernicharo, 2006). Treatment of domestic wastewater in sequential anaerobic–aerobic processes exploits the advantages of the two systems in the most cost-effective set-up. In comparison with conventional aerobic technologies, the combined anaerobic–aerobic system consumes distinctly less energy, produces less excess sludge and is less complex in operation (van Haandel and Lettinga, 1994; von Sperling and Chernicharo, 2005).

In the anaerobic system, solids are entrapped and organic matter is converted into biogas consisting mainly of methane and carbon dioxide. Organically bound nitrogen is converted to ammonium and sulfate is reduced to hydrogen sulfide. Sludge production in anaerobic systems is low and the excess sludge is already digested and can be directly dewatered, typically by drying beds. Regarding the microbiological indicators, coliform removal efficiency is low in anaerobic systems (Keller et al., 2004; Pant and Mittal, 2007). However, helminth eggs are removed more effectively, particularly in the upflow anaerobic sludge blanket (UASB) reactor (Gerba, 2008). Anaerobic effluent’s residual concentration of suspended solids and organic matter is polished in the aerobic system, along with ammonium oxidation to nitrite/nitrate via nitrification. Depending on the type of process and the operational conditions, aerobic treatment provides about 1–2 log pathogens removal (von Sperling and Chernicharo, 2005).

Nitrogen level adjustments can be incorporated in sequential anaerobic–aerobic system through partial recirculation of the

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nitrified aerobic effluent to the anaerobic reactor for denitrification to take place in conjunction with anaerobic digestion. In the integrated anaerobic reactor part of the organic carbon content in the raw wastewater serves as carbon source for denitrification and the rest is converted to methane. The proposed set-up is particularly of interest for concentrated wastewaters and/or lower ambient temperatures as under those conditions the volumetric design is not limited by the hydraulic loading rate (van Lier, 2008), i.e. there is already a volumetric spare capacity available to accommodate the recirculated flow.

To put the sequential anaerobic–aerobic treatment options on view and to state their feasibility and efficiency in domestic wastewater treatment, a desk review of the researched anaerobic–aerobic systems was performed with accentuation on high rate systems. The sequential systems were classified according to the mode of growth in the aerobic reactor i.e. suspended growth versus attached growth systems.

2. Sequential anaerobic-suspended growth aerobic systems

In the spectrum of suspended growth treatment processes, Activated Sludge (AS) is the most common configuration. By definition, the basic AS process consists of two basic units: (1) a reactor in which the microorganisms responsible for treatment are kept in suspension and aerated and (2) a liquid solids separation unit. An essential feature of the process is recirculation of part of solids removed from the liquid solids separation unit back to the aeration unit to maintain a high concentration of microorganism in the aeration tank.

A sequential system consisting of anaerobic baffled reactor (ABR) followed by an AS system was proposed by Garuti et al. (1992) for the treatment of domestic sewage. The proposed ABR comprises of: two anaerobic sludge blanket sections, an anoxic sludge blanket section and sludge trap section. Part of AS effluent is recycled to the anoxic section of the ABR to achieve denitrification. This configuration (Fig. 1a) with its ANaerobic, ANoxic and OXic sections (ANANOX) prevents biomass transfer, and thus it can be classified as a “separate biomass” system. Investigations on a pilot scale system resulted in achieving removal efficiencies of 90% for the total COD, 90% for the total suspended solids (TSS) and 81% for the total nitrogen (TN). Produced excess sludge was limited to 0.2 $\mathrm{kgTSS\ kgCOD_{removed}^{-1}}$. Once the successful operation of the ANANOX system was ascertained in pilot scale, its application on full scale took place (Garuti et al., 2001) with 30 m^3 ABR, 15 m^3 aeration tank and 32 m^3 secondary clarifier. At best operating conditions, total COD removal efficiency of 95% and TSS removal of 92% was achieved. The percentages of organic load removed by the anaerobic, anoxic and aerobic phases were 33%, 20% and 48%, respectively. It should be realized that this performance was obtained at a fairly low organic loading rate of 0.97 $\mathrm{kgCOD\ m^{-3}\ d^{-1}}$ on the first anaerobic section. Apparently, the system is not optimized with regard to anaerobic phase efficiency. By means of nitrification, 80% conversion of ammonium was achieved in the aerobic stage and at a recycle to feed ratio of one, 58% of nitrate applied to the anoxic section was denitrified.

The feasibility of the ANANOX system for effective carbon and nitrogen removal from domestic wastewater has been evidently illustrated. However, ABRs encounter hydrodynamic limitations, which in turn impose constrains on achieving long sludge retention times (SRT) (van Lier et al., 2008). This makes the ANANOX system less favorable. However, its potentiality for simultaneous removal of carbon and nitrogen, owing to the fact that denitrifiers and methanogenesis can be cultivated separately, intensify its prospects. Nevertheless, under the condition that denitrifiers and methanogenesis are successfully integrated in a UASB reactor, which is capable of maintaining long SRT at relatively short HRT, an integrated system consisting of UASB reactor followed by an aerobic reactor, with partial recirculation of aerobic effluent to the UASB reactor to achieve denitrification, likely out competes the ANANOX system.

Combining an AS system with an UASB reactor was suggested by many researchers (e.g. von Sperling and Chernicharo, 1998). If compared with conventional AS system, less energy is consumed and much less excess sludge will be produced. For the sake of comparison von Sperling and Chernicharo (2005) presented designs of conventional AS system and combined UASB–AS system, using the same input data, i.e. low strength domestic wastewater with a BOD_5 amounting to 340 $\mathrm{mg\ l^{-1}}$. Results have shown that preceding the AS system with a UASB reactor resulted in 60% reduction in sludge production and 40% reduction in aeration energy consumption. Furthermore, the UASB reactor acts as an influent equalization tank and it substitutes the primary clarifier.

The configuration of UASB–AS system is also interesting because it highlights the possibility of upgrading existing AS plants by installing a UASB reactor before the aeration tank (Halalsheh and Wendland, 2008).

Von Sperling et al. (2001) reported results from 261 days of operation of a UASB reactor followed by an AS system under tropical conditions (Table 1). The UASB reactor had a volume of 416 l, feeding besides the AS system other post treatment lines, while the aeration tank had a volume of 23 l. The overall system (Fig. 1b) achieved at total HRT of 7.9 h, of which 4 h UASB, 2.8 h aeration tank and 1.1 h final clarifier, a total COD removal efficiency ranging between 85% and 93%. The percent of COD removed by the UASB reactor, relative to the COD removed by the overall system was in the range of 81–94%. An interesting point clarified in this study is the fact that in consequence of by-passing 20% of raw sewage to the AS, bulking problems systematically resulted while it was only occasional in case of applying UASB effluent only.

Under low to moderate temperatures ranging between 15 and 30 °C, Motta et al. (2007) investigated the performance of UASB–AS system with recirculation of excess activated sludge to the UASB reactor for digestion (Table 1). UASB reactor of 396 l was operated at an HRT of 3.2 h. The influent had average total COD of 341 $\mathrm{mg\ l^{-1}}$, bringing about an OLR of 2.6 $\mathrm{kgCOD\ m^{-3}\ d^{-1}}$. The up flow velocity was maintained at 1 $\mathrm{m\ h^{-1}}$ through internal recirculation. The AS system was tested at an aeration chamber’s HRTs of 2 and 3 h, which, in consequence of the UASB reactor performance, resulted in F/M ratios of 1.5 and 0.9 $\mathrm{kgCOD\ kgVS\ S^{-1}\ d^{-1}}$, respectively. Keeping a constant flow rate, the aeration tank was operated at different HRT by volume adjustments. The tank volume used to achieve 2 h HRT was 240 l, and that used to achieve 3 h HRT was 360 l. The overall system (Fig. 1c) achieved 87% total COD removal efficiency and 92% TSS removal efficiency, regardless of the aeration chamber’s HRT. Nevertheless, increasing the HRT from 2 to 3 h in the aeration chamber resulted in more stable operation including better particle flocculation and better sludge settling characteristics. The contribution of the UASB reactor to the total COD removed by the overall system was limited to 34%. Production of methane relative to removed COD was on average 0.1 $\mathrm{m^3\ kgCOD_{removed}^{-1}}$. The authors have stated that in spite of the UASB reactor low removal efficiencies, the performance of the overall system was satisfactory since the secondary effluent water quality requirements were met. Nevertheless, optimizing the operation of the UASB reactor through increasing the HRT and reducing the up flow velocity would reduce the load on the subsequent AS system resulting in less consumption of energy and less production of excess activated sludge.

Based on the outputs of the Brazilian Research Program on Basic Sanitation (PROSAB), von Sperling and Chernicharo (2005) pre-