Anaerobic treatment of domestic sewage: established technologies and perspectives

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Abstract The use of anaerobic reactors for domestic sewage treatment has increased significantly since the UASB configuration started to be efficiently applied for this purpose in the beginning of the 1980s. Nowadays, hundreds of UASB reactors, or similar anaerobic units, are used in domestic sewage treatment systems, particularly in developing countries. These units have been operated at ambient temperature, normally higher than 20°C, at hydraulic detention time in the range of 6 to 10 hours, and organic loading rates lower than 3.0 kg $COD.m^{-3}.d^{-1}$. They have presented COD removal efficiencies in the range of 65% to 80%. Besides, new configurations have been developed and assayed in research centres, aiming to amplify the range of application and to improve process performance. At the same time, research is being conducted on the post-treatment of anaerobic effluents attempting to offer alternatives to the existing conventional systems. It takes into consideration not only sanitation and environmental protection, but also considers resources conservation at lower construction and running costs as the main supporting concepts for further development. This text presents some aspects of the consolidated technologies and suggests on further developments in the conception of domestic sewage treatment systems having the anaerobic process as their core.

Keywords Anaerobic process; domestic sewage; nutrient removal; post-treatment; UASB reactor

Introduction

Recent developments in anaerobic processes for wastewater treatment have to be credited to the success of the UASB reactor concept (Lettinga *et al.*, 1980). First proposed for the treatment of high strength industrial wastewaters at mesophilic temperature, UASB configuration satisfies the main characteristics required for biological treatment systems to be simple and efficient: i) high biomass concentration inside the reactor, propitiating high cellular retention times; ii) development of structured multi-cellular aggregates in the form of granules or dense sludge, composed of different species and microorganism groups responsible for the conversion of organic matter into methane and carbon dioxide; iii) low requirement of nutrients and low excess sludge production; iv) high stability in response to normal fluctuations of influent composition and concentration; v) capacity of accommodating high organic loading rates (OLR). Besides, the costs of construction, installation, and operation are lower than those of conventional aerobic units because the reactor does not require equipment for process maintenance and control. In fact, if the environmental conditions inside the reactor are adequate, anaerobic processes are mainly self-controlled. Additionally, the production of excess sludge is minimal, and energy balances are quite favourable due to the production of methane, even when heating is required.

The performance of the UASB configuration treating industrial wastewaters, at the mesophilic temperature range and high OLR, induced researchers to apply it to domestic sewage treatment at the beginning of the 1980s. As a consequence, the use of UASB reactors spread to many countries (Brazil, Mexico, Colombia, Cuba, Uruguay, among others). The first results from the application of UASB reactors for domestic sewage treatment were quite contradictory. In many cases, the expected performance was not achieved and distrust of the anaerobic process increased due to the bad odours produced in some plants.

In fact, there are significant differences between domestic sewage and the industrial wastewaters commonly treated in UASB reactors at that time. Although considered low-strength wastewater, domestic sewage is quite complex due to the high fraction of particulate COD, presence of fatty compounds, proteins, and detergents, among other barely known compounds. These characteristics impose limitations on the anaerobic process in respect to COD removal efficiency, and also in terms of the maximum organic (OLR) and hydraulic loading rates (HLR) to be applied. These limitations impose the need for post-treatment in many situations, besides the special attention in designing to avoid hydraulic overloading and to allow odour control.

Another significant difference is related to the low amount of methane that can be recovered from organic matter decomposition in some cases. For low-strength wastewaters, especially domestic sewage, the energy balance is favourable only if heating can be avoided. It occurs in tropical regions where the reactors can be operated at ambient temperatures, usually higher than 20°C.

The favourable environmental conditions, the extreme deficit in sanitation, and the need for development of low-cost systems to face financial constraints were the main factors leading to the implementation of the anaerobic technology in Brazil.

Established technology

After the uncertain beginning in the 1980s, the applicability of anaerobic reactors for the treatment of domestic sewage is definitively established in tropical regions. This means that if correctly designed and operated, anaerobic reactors can be considered trustworthy and stable after the start-up period.

There is no report in the literature on process collapse due to imbalances in the production and consumption of volatile fatty acids (VFA) in anaerobic reactors treating domestic sewage. It is well known that imbalance in the production and consumption of VFA is the main intrinsic factor affecting process stability in the treatment of high-strength wastewater. However, the VFA production is not significant in low-strength wastewater treatment, and VFA concentrations are always below the inhibitory limits permitting the methanogenic process to be progressively established. In fact, instability of anaerobic reactors treating domestic sewage has always been related to hydraulic overloading or mistakes in reactor design or operation. Therefore, process instability can be avoided if convenient values of HLR are applied. In tropical countries, the liquid temperature is usually high enough for the reactor to be operated without heating. These conditions make the energy balance completely favourable in comparison with conventional aerobic systems.

UASB reactors have been successfully used as the first unit of the systems designed for domestic sewage treatment at ambient temperatures higher than 20°C. COD removal efficiencies of 65% to 80% have been obtained at an applied OLR of usually lower than 3 kg COD. $m^{-3}.d^{-1}$, and HDT ranging from 6 to 10 hours (Rodriguez *et al.*, 2001; Florencio *et al.*, 2001; Passig *et al.*, 2000; Torres and Foresti, 2001; Chernicharo and Nascimento, 2001). HDT can be reduced depending on two factors: the quality of the effluent accepted by post-treatment units and more favourable thermal conditions. In tropical regions where mean temperatures are close to 25°C or higher, HDT lower than 6 hours has been practiced, without any significant impairment in the reactor's performance.

The start-up period has been considered a crucial step for the stable operation of anaerobic reactors at the designed OLR. One of the main points frequently stressed is the need for the reactors to be inoculated with high quality methanogenic sludge. Recent case studies on full-scale anaerobic reactors treating domestic sewage have shown that inoculation can be neglected (Passig *et al.*, 2000). Even very poor anaerobic sludge can be used as inoculum (Rodriguez *et al.*, 2000). However, it has been verified that the start-up period can last up to six months if no inoculums are added.

Granulation has been also observed in UASB reactors treating domestic sewage. Such a feature probably indicates that the selection pressure can be less dependent on the predominance of carbohydrates in the wastewater composition. It is possible that the up-flow stream in such reactor configurations is the main factor favouring the granulation process that can occur, depending on the ascendant velocities in the sludge bed.

There are some aspects related to the performance of anaerobic reactors treating domestic sewage that still deserve to be clarified. One of them refers to the effluent composition. Even at OLR lower and HTD higher than the values presented above, the filtered effluent COD stands in the range of 80 to 120 mg.l^{-1}. This inferior limit is likely to be independent of the reactor configuration and of the value of the influent COD. A very small fraction is probably due to VFA (~20 mg.l^{-1}). In such cases, it probably results from mass transfer limitations. But the remaining fraction still needs to be identified properly. Therefore, the effluent COD possibly provides better information on the performance of the reactor than the COD removal efficiencies obtained.

Besides UASB reactors, other configurations have been investigated such as: fluidised bed reactors, baffled reactors (Lopes and Campos, 2000), horizontal-flow anaerobic immobilized biomass reactors (Zaiat *et al.*, 2000), and sequencing batch reactors (Cybis and Pescado, 2000; Callado and Foresti, 2001). Although presenting potential for application, the results are mostly based on bench- and pilot-plants. It is worth mentioning that a system composed by septic tank followed by anaerobic filter has been used since the 1980s in Brazil for the treatment of domestic sewage from small communities. It is being investigated again in order to improve its design and to amplify its application (Andrade Neto *et al.*, 2000).

Post-treatment of anaerobic effluents

Effluents from anaerobic reactors treating domestic sewage can rarely comply with the emission standards. Besides the remaining fraction of particulate and soluble organic matter, the main important constituents or components deserving attention are nutrients and pathogens. They are not removed efficiently in the most commonly used anaerobic reactors.

In Brazil, a specific program (PROSAB – Program on Basic Sanitation) on the post-treatment of effluents from an anaerobic reactor is being carried out, supported by the government, involving twelve research institutions. It aims to investigate appropriate post-treatment technologies considering the diversity of environmental and socio-economic conditions in distinct regions of the country. The alternatives include: soil/plant systems; ponds; biofilm reactors; activated sludge systems; dissolved-air flotation systems; filtration units. Details of the main PROSAB results are presented in Chernicharo *et al.* (2001). For this reason, they are omitted in this text except in aspects concerning the association of anaerobic reactors with SBR – aerobic sequential batch.

This association forms a very compact and flexible system that can be used for the removal of the remaining COD and TSS. If aeration time is higher than four hours, nitrified effluents can easily be obtained (Sousa and Foresti, 1996; Torres and Foresti, 2001). The anaerobic reactor can receive the aerobic sludge discharged from the SBR without affecting its performance. In that case, the excess sludge is discharged from the anaerobic reactor. It is very stable, dries easily, and represents a very small fraction of the total mass of organic matter removed (Sousa and Foresti, 1996). If the reaction step of the SBR is properly operated under aerobic/anaerobic sequences, and an external carbon source is added, nitrification, denitrification and biological phosphorus removal can occur in the same cycle (Callado and Foresti, 2001). In that case, the phosphate-enriched sludge cannot be returned to the anaerobic reactor, and the aerobic sludge is discharged from the SBR. Although successful, experiments on such systems have been carried out in bench-scale and pilot plants, and there are several aspects that deserve attention for full-scale application.

Growth of the aerobic sludge in the SBR is very slow due to the low concentration of readily biodegradable substrate for the aerobic process. This results in long start-up periods of the aerobic SBR. Once adapted, the aerobic biomass is able to produce completely nitrified effluents.

Simultaneous denitrification and biological phosphorus removal depends on the addition of an external carbon source at the beginning of the anoxic phase in a batch cycle. The amount of the external carbon added is stoichiometrically proportional to the amounts of influent nitrogen and phosphorus. This can represent an important drawback for the implementation of such a system, since there are aerobic/anoxic processes for the treatment of domestic sewage that avoid the use of an external carbon source. However, there are some possibilities of using by-products of the earlier treatment steps for this purpose. Methane is one of the by-products that can be utilized for denitrification, but it has not been tested for biological phosphorus removal so far.

The best external carbon source for both the processes seems to be acetate (Callado and Foresti, 2001), one of the metabolic products of the fermentation step in the anaerobic process. Being a direct precursor of methane, acetate is readily utilized just after being produced in methanogenic reactors. Therefore, if it has to be used for a purpose other than methane production, the methanogenic step has to be suppressed and the best conditions for acetate production have to be imposed.

One possible source of acetate could be the controlled hydrolysis and fermentation of primary sewage sludge. According to this system concept, primary sludge and fatty material are separated before the anaerobic reactor and sent to a hydrolysing/fermentation chamber for producing VFA. The liquid fraction from this chamber can be added to the aerobic SBR providing the external source of carbon for denitrification and phosphorus removal. The sludge fraction can be sent to an anaerobic digester to complete the stabilization process before being disposed of. Although it increases the system complexity, the anaerobic treatment of liquid and sludge in separate reactors can be advantageous in some cases.

Phase separation has been proposed for the applicability of anaerobic process treatment of domestic sewage at low temperatures (Wang, 1994). Considering hydrolysis as the limiting step, the alternatives already studied include a previous suspended solids (SS) separation step. According to Elmitwalli *et al.* (2001), the retention and hydrolysis of SS in the first reactor improved the performance of a system composed of two sequential anaerobic reactors treating domestic sewage. The authors attributed it to the high removal of the COD colloidal fraction in the second reactor (hybrid anaerobic reactor).

Seghezzo *et al.* (2000) presented results on the use of UASB reactor treating pre-settled sewage. The mean monthly sewage temperature ranged from 16°C (winter) to 25°C (summer). COD removal efficiencies higher than 50% were obtained, and the mean effluent COD was 72 $\mathrm{mg.l^{-1}}$. Such effluent COD value is low considering process limitations, inferior than those obtained without previous SS separation.

Some fixed bed anaerobic reactors are not used for raw domestic sewage treatment as the SS usually provokes bed clogging. That is the case of up-flow anaerobic filters (AF) and horizontal-flow anaerobic immobilized biomass (HAIB) reactors. However, a previous separation of part of the suspended solids and fatty material would permit better use of these reactors, including the retention and degradation of the colloidal COD fraction.

One of the most important aspects in respect to the establishment of the anaerobic technology is the amplification of low-cost alternatives for domestic sewage treatment. It is well known that low-cost systems were frequently associated with the availability of large areas to be occupied by ponds or similar systems in tropical regions. This understanding has being changed with the implementation of the anaerobic technology. As most of the organic matter fraction can be removed in a single reactor, the system can be very compact, depending on the required effluent quality. Compact and easy operation plants tend to substitute the centralized ones, frequently more distant from the cities, and for this reason, dependent on complex and expensive sewage transportation systems.

Conclusions

The performance of UASB reactors in the treatment of domestic sewage permits to consider the anaerobic biotechnology to be established in tropical regions where the ambient temperature is higher than 20°C. The main design parameters are already set up, and the reactor performance after the start-up period can be predicted with reasonable security. Other anaerobic reactor configurations have presented similar performance at bench- and pilot-plants, but the results have to be confirmed in full-scale plants.

The post-treatment of anaerobic effluents has been extensively studied in bench- and pilot-plants. The amplitude of alternatives has increased significantly ranging from very simple systems (such as ponds) to multi-functional reactors (such as SBR). Consequently, treatment systems having the anaerobic process as their core can be applied to satisfy even the most restrictive standards for effluent discharge.

The success obtained with phase separation systems in the treatment of domestic sewage at low temperatures enhanced the importance of the hydrolysis step. Although less important for the anaerobic treatment at ambient temperatures in tropical regions, phase separation can be utilized to enhance the performance of methanogenic reactors. It also favours the utilization of fixed-bed anaerobic reactors, and can probably be better utilized for the production of the compounds needed for nutrient removal.

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