BIOLOGICAL PHOSPHORUS REMOVAL IN FIXED FILMS REACTORS

R. Franci Gonçalves and F. Rogalla

ANJOU RECHERCHE, Research Center Compagnie Générale des Eaux - OTV, Chemin de la Digue, F78600 Maisons Laffitte, France

ABSTRACT

Possible procedures to achieve biological phosphorus removal in a fixed film reactor are discussed and the feasibility of phosphorus removal process in a fixed film reactor under continuous flow is demonstrated. The behaviour of an upflow aerated filter operating under continuous feed and alternate aerobic / anaerobic conditions is analyzed. The influence of the duration of anaerobic and aerobic contact periods and of organic substrate loadings on the phosphorus removal process is verified. During the anaerobic state, the longer the duration, or the higher the substrate load, the better the phosphorus release and consequently the higher the uptake in the aerobic phase. The excess of accumulated phosphorus in the aerobic phase over released phosphorus in the anaerobic phase approaches 33 %. For each mg of phosphorus released, 5 mg filtered COD are consumed.

Continuous phosphorus removal on two biofilters in series was performed by alternating aeration conditions, always introducing the influent to the anaerobic reactor. The tests carried out on laboratory scale showed that this system carries out complete nitrification and removal of 80% of the phosphorus with a maximum hydraulic retention time of 5 hours. The hydraulic retention time and the residence time of the biomass in the reactor are independent and, therefore, the time the bacteria are exposed to alternate A/O conditions can be optimized. The very low concentrations of suspended solids in the effluent of the biofilter enable residual levels below 1 mg PO₄-P/l to be obtained. Further investigations are carried out on full scale and to introduce denitrification in the same reactor.

KEYWORDS

Biofilm, phosphorus removal, coastal regions, aerated filter, floating bed

INTRODUCTION

Phosphorus and nitrogen discharges in progressively increasing quantities disturbs the ecological balance and creates undesirable conditions in inland waters, estuaries and coastal marine waters. To prevent eutrophication, the new European Community Directive of March 1991 imposes very stringent limits on nutrient levels in wastewater discharges. For many inland receiving waters, including North, Baltic and Adriatic Seas, nitrogen and phosphorus will have to be eliminated. To upgrade existing facilities in accordance with the legislation and to integrate in the new context some coastal regions where environmental infrastructure has been neglected intense construction programs are necessary.
In the last few years great efforts have been made to increase in efficiency and quality the conventional biological treatment processes. Nitrification and denitrification can be achieved in the new configurations of activated sludge plants by using either alternate anoxic/aerobic zones or two stage solutions, allowing a reduction in the necessary reactor volume (Cooper et al., 1977). Total nutrient removal can be achieved by associating nitrification/denitrification with phosphorus removal by physico-chemical means, advanced biological treatment or a mixture of both (Bundgaard and Petersen, 1990).

The physico-chemical processes are an effective technique, ensuring effluent P-levels of < 1 mg/l (Boller, 1984), but the additional costs of reagents and the increase in the sludge production makes biological treatment an attractive alternative. Complete biological removal of nitrogen and phosphorus requires the introduction of an anaerobic zone in the nitrifying/denitrifying activated sludge plants, and strict plant control is necessary to attain low residuals (Tetreault et al., 1986). Practical experience shows that effluent concentrations of 2 mg P/l can be reached by biological means if organic substrate conditions are favourable in the influent and if an excellent secondary settler is available. In combination with a small dosage of chemical precipitants, stable effluent P-levels of the order of 1 mg P/l can be attained (Ketchum et al., 1987). If lower effluent residuals have to be reached, effluent polishing by tertiary filtration is necessary. Because phosphorus and nitrogen removal often require additional unit processes, these facilities need a great deal of space, and, thus, their implementation may be difficult in densely urbanised coastal areas where land is unavailable.

To reduce land area requirements and reactor volume many efforts have been made in the past few years to develop high-rate biological fixed film processes. Biological aerated filters (BAF) have gained acceptance as compact and simple wastewater treatment plants, combining aeration and clarification in one unit (Rogalla et al., 1991). The absence of downstream clarification makes the process independent of the sludge settling properties, providing high biomass concentrations on the granular media. The BAF are particularly efficient in secondary and tertiary nitrification (Rogalla et al., 1990) and total nitrogen removal is possible by recycling the nitrified effluent into an anoxic filter, similar to nitrification and denitrification in the single stage activated sludge plant (Gilles and Bourdon, 1985). Phosphorus removal has been restricted in this system to physico-chemical precipitation and separation in the primary settler, achieving very low residuals in the effluent in one compact unit (Kantardieff, 1989).

The high biomass concentration and the high ability to retain suspended solids in the reactor allow us to foresee the high performances in biological phosphorus removal by the BAF. However, biological phosphorus removal using fixed film processes is comparatively rare and performed mainly on laboratory-scale tests. The major objective of this paper is to present the first application of biological phosphorus removal in a fixed film reactor with a continuous feed and the limiting parameters are established in regard to biofiltration technology.

PHOSPHORUS REMOVAL MECHANISMS

Biological phosphorus removal is based on the accumulation of this element in the biomass beyond its metabolic needs for growth. Two main requirements must be complied with in order to ensure the process: biomass have to be exposed to cyclic alternation of anaerobic/aerobic (A/O) conditions, and, in the anaerobic contact period, the reactor must contain sufficient amounts of simple organic substrates (in particular volatile fatty acids - VFAs). During the anaerobic contact time, the phosphorus removing bacteria use intracellular reserves of polyphosphates as a source of energy and store simple organic substrates. This causes the release of the phosphorus in the anaerobic zone. On the following aerobic contact period, bacteria use the reserves of carbon as an energy source and accumulate more phosphorus than that released previously. A strict anaerobic contact time is essential in the process, and the presence of nitrates in the anaerobic zone interferes with phosphorus release. Maximizing the application of simple readily biodegradable organic substrates (in particular VFAs) during the anaerobic phase increases the efficiency of the process (Fuhs and Chen, 1975; Nicholls and Osborn, 1979; Marais et al., 1983; Comeau et al., 1986).

All industrial-scale applications of biological phosphorus removal are variations of the activated sludge system. In this system, the biomass is transported in the reaction zones where environmental conditions (A/O) ensure the activity of the phosphorus removing bacteria. The biomass in the reactors is constantly...
Biological phosphorus removal 167

renewed by the recirculation of the sludge and, consequently, continuous feeding of the system is possible. In a biofilm reactor, because of the fixed state of the biomass, the only solution is to alternate conditions (A/O) in time, by start-up and shutdown of the aeration. Continuous flow biofilm reactors appeared to be until now impossible, because biofilm cannot be transported like in the activated sludge. The same attached bacteria are exposed firstly to anaerobic conditions and then to aerobic conditions, and the biomass in the reactor is not renewed during one cycle A/O. The required conditions being provided in a time sequence, the extraction of the phosphorus trapped in the biofilm is operated during filter washing, at the end of an aerobic period.

MATERIAL AND METHODS

The tests have been carried out until now in laboratory-scale pilots. The reactor consists of submerged floating filter, held in immersion by a nozzled plate. A co-current water and air flow is applied to the filter. The filter is 0.20 m in diameter and 3.00 m high. The filter media of polystyrene beads, with an effective diameter of 2.2 mm, varies in bed-height between 1.00 and 1.50 m. The alternation of the A/O conditions is activated by a set of solenoid valves controlled by an hourly programmable timing unit.

The experiments were carried out with wastewater from a combined urban sewer, after screening, lamella settling and storage in a homogenization tank for about 3 hours. Its characteristics are shown in table 1 and the analysis techniques are the ones recommended by AFNOR.

The experimental plan was devised in three different parts. In the first part, the behaviour of the biofilter exposed to systematically alternate A/O conditions was studied. The kinetics of the nutrient removal process, with emphasis on the phosphorus removal process, were analysed with the reactor operating under batch and dynamic conditions. Various A/O cycles, with different durations and A/O ratios, were tried. During the tests with certain A/O cycles, the influence of different organic loading rates was examined. After each modification on operational conditions of the reactor two weeks were allowed for biomass adaptation to the new conditions.

In the second part, two identical filters operating in series were studied (figure 1). The first reactor was fed with settled urban wastewater and held under anaerobiosis. The aerobic filter received the effluent of the anaerobic filter and completed the treatment. In order to ensure the phosphorus removal process, at the end of one specific interval of time (3 to 12 hours) the A/O conditions were reversed. The direction of the flow was also reversed, in order to always keep the feeding of settled wastewater to the anaerobic reactor (figure 2). During this period various durations of A/O cycles and organic loading rates were applied.
The third part of the study is still being carried out and consists of the study of the association of several filtration units (4 to 6), by introducing one or more anaerobic phases into the cycle of filtration of each unit, in order to optimize the complete nutrient removal (C, N and P) by strictly biological means in a wastewater treatment plant.

RESULTS AND DISCUSSION

Figure 3 shows the typical behaviour of a biofilter operating under alternate A/O conditions and continuous feeding. The tests were carried out with the filter already under steady state with regards to the biological processes of nutrient removal (C, N and P). In the following example the tests had an A/O cycle which lasted a total of 12 hours, with an anaerobic phase of 6 hours and an aerobic phase of 6 hours. The organic loading rate to the reactor was of the order of 4 kg COD/m$^3$/day.

Anaerobic phase

During the first two hours of this phase a rise in the phosphate concentration is observed in the filter effluent. The rate of rise in concentration in the effluent is initially moderate reaching a maximum value during the second hour of anaerobiosis. At this point the concentration of phosphates in the effluent reaches values of the order of 30 mg PO$_4$-P/l or more. These levels then drop progressively until the end of the phase. In the tests with longer anaerobic phases (8 and 12 h) the phosphate concentration at the end of the phase approaches that in the filter influent.

Immediately after the aeration stopped ($t=0$ h) the level of NH$_4$-N in the effluent, which is initially low, increases at a constant rate equivalent to the ammoniacal nitrogen loading rate in the influent. It reaches a maximum value equal to the influent concentration in the first hour of operation. Since the nitrification stops completely, the ammoniacal nitrogen fed into the filter does not undergo any modification and is found in the effluent of the reactor.

A rapid denitrification takes place in the first hour of anaerobiosis. The beginning of the maximum P-release rate coincides with the moment the nitrate concentrations in the effluent drop under 5 mg NO$_3$-N/l. This happens towards the end of the first hour of anaerobiosis when the oxidation reduction potential reaches values of - 150 mV (Ag/AgCl).

![Figure 3. Typical behaviour of a BAF operating under alternate A/O conditions and continuous feeding](https://iwaponline.com/wst/article-pdf/25/12/165/14738/165.pdf)
The soluble COD concentration also increases in the effluent during the anaerobic phase. It increases at a constant rate which is lower than the soluble COD loading rate to the filter. The difference between the two rates corresponds to the sol COD uptake by the fixed biomass during anaerobiosis.

**Aerobic phase**

As soon as the aeration starts, the fixed biomass takes up the phosphate available in the reactor at a fast rate. It is possible to obtain an effluent with very low levels of phosphate as early as the end of the first hour of the aerobic phase. The phosphate concentrations in the effluent at the end of the phase may rise to the same values of the influent, depending on the load applied to the reactor. For the long aerobic phases and high P loading rates the concentrations of phosphate in the effluent at the end of the phase are similar to the levels entering the filter.

At the same time, the dissolved oxygen concentration quickly stabilizes at 5 to 6 mg O$_2$/l and the levels of NH$_4$-N and soluble COD drop rapidly at the beginning of the secondary nitrification.

**Comparison between dynamic and batch tests**

A comparison between a batch test and a test with continuous feeding for the aerobic and anaerobic conditions is shown in figure 4. The behaviour of the fixed biomass under batch conditions agrees with the description of batch tests with suspended biomass carried out by other authors (Wentzel et al., 1985; Tsuno et al., 1987).

A fast release of PO$_4$-P and a rapid COD uptake characterize the first hours of the anaerobic test. A progressive stabilization of the COD and PO$_4$-P concentrations after the first two hours indicate that the biomass released the necessary amount of phosphorus to promote the anaerobic uptake of carbon substrate available at the beginning of the test. A constant ratio between the amount of COD taken up and the amount of phosphorus released was observed in most of the anaerobic tests: 5 mg sol. COD / mg P released.

Aerobic batch tests are characterized by a rapid P removal from the bulk liquid in the first hour of aeration. When a high concentration of P is available for uptake by the biomass (a test non limited in P), the rate of P uptake diminishes with the time, reaching a constant value at the end of the test. At this point the biomass has completed its stock of polyphosphates and reached a saturation level in P.

The release and uptake of phosphorus in time can be described by kinetics of order one. As illustrated by the previous example, this corresponds to a drop in the activity of the phosphorus removal bacteria during each phase, with the maximum degree of activity being observed at the beginning of the phase.
The behaviour of the biofilter under continuous feed can be explained by the kinetics of the phosphorus removal and the hydraulic conditions of the reactor. While the rate of P uptake or release by the biomass (at the beginning of the test) is greater than the P loading rate to the reactor, the tendency of phosphorus concentrations in the effluent of the reactor agree with the results of the batch tests: rise in the case of anaerobiosis and drop in the case of aerobiosis. From the moment the bacterial activity drops to levels below the P loading rate to the filter, a dilution occurs and a tendency contrary to that expected is observed.

**Possible operational procedures for a phosphorus removal biofilm reactor**

**SBR Procedure** - biological phosphorus removal can be achieved in any fixed reactor by adopting an operational procedure similar to the sequencing batch reactors (SBR). In this case a cycle consists of: fill, react (anaerobiosis and aerobiosis) and draw of the treated effluent. This was successfully tested on a laboratory-scale BAF by Gonzalez-Martinez and Wilderer (1990). However, two limiting situations may arise with regard to the biological phosphorus removal process. During the anaerobic phase, a limited availability of carbon source at the beginning of the test, depending on the influent characteristics, limits the degree of P release. In the aerobic phase, the phosphorus load instantaneously introduced at the beginning seems to be lower than the maximum uptake capacity of the biomass.

**Batch anaerobic phase and continuous feed aerobic phase** - this procedure was adapted for a BAF by Yoon and Suzuki (1990). Maximum advantage can be taken of the P uptake capability during the aerobic phase by continuous P loading to the reactor. However, the problem of limiting the anaerobic P release, and hence the whole process, persists when domestic wastewater of average characteristics is used to feed the reactor.

**Continuous feed throughout the A/O cycle** - in an attempt to eliminate both limiting conditions previously discussed, the reactor was put under continuous feed conditions. This enables an optimization of the applied organic load according to the needs of the biomass during anaerobiosis and also of the P load to be removed during the aerobic phase. The remaining problem of bad effluent quality during the anaerobic phase was solved by using two filters in series as shown in figure 2. The effluent quality during a complete A/O cycle, with an anaerobic phase of 6 hours and an aerobic phase of 6 hours, is presented in figure 5.

![Figure 5 Effluent characteristics during a complete A/O cycle (6 x 6 hs) - part II](https://iwaponline.com/wst/article-pdf/25/12/165/14738/165.pdf)
The first filter, in relation to the direction of flow, functions exactly as an anaerobic filter as far as carbon and nitrogen pollution are concerned: a moderate carbon uptake and no action upon the influent nitrogen. A high P release takes place from the second hour of the anaerobiosis, when the bulk liquid has no nitrates and real anaerobic conditions prevail in the reactor. The second filter, in aerobiosis, further oxidizes the organic material and ammoniacal nitrogen. It also takes up all the P load released by the first filter and all the P load applied to the filter. To achieve an effluent with total P < 1 mg/l, during the whole of the aeration period of one same filter, the applied P load must not exceed the over - accumulation capacity of the fixed biomass (figure 6).

\[ y = 1.33x + 12, \quad r^2 = .96 \]

Figure 6. Ratio between total phosphorus uptake during aerobiosis and total phosphorus release during anaerobiosis

Figure 7 shows the performance of the system in relation to removal of suspended solids from the influent. Throughout the whole period of tests the reactor produced systematically an effluent with < 10 mg TSS/l. This feature is essential for a phosphate removing system because it limits the amount of P leaving the reactor by the loss of biomass rich in P. Analyses of the biomass at the end of the anaerobic phase show that the levels of P can reach 4 to 5% of the total weight. This means that at the most 0.5 mg P/l in the effluent will be due to the loss of suspended solids.

Figure 7. Retention of total suspended solids in the BAF
Main conclusions taken from part 1 and 2 of the experimental plan

- Continuous biological phosphorus removal in a BAF is possible by associating two or more reactors in series, as shown previously.

- In the cases where a low organic load is applied (< 5 kg COD/ m³ anaerobic bed / day), the long anaerobic phases favor P release and, therefore, increase the efficiency of the process. The table 2 shows the development of total PO₄-P release during the anaerobic phase as a function of the duration of the phase.

- Cycles with short anaerobic phases (4 to 6 hours) may have a limited PO₄-P release, when the organic load is < 5 kg COD / m³ anaer. bed / day. Combining high organic loads (> 15 kg COD / m³ anaer. / day) and short anaerobic duration causes the same release as when weak loads and long durations are applied (table 3). The total availability of COD during anaerobiosis was almost the same in both cases (total weight of COD).

- A drop in the efficiency of nitrification proportional to the duration of the anaerobic phase was observed during the first part of the study (table 2). During the cycles with anaerobic phases of 12 hours nitrification stopped almost completely. In the second part of the study, when the filters were operated in series, the reduction of the organic load by the anaerobic filter made nitrification in the aerobic filter easier, reducing considerably the impact of long anaerobic phases on the process.

Table 2. Total PO₄-P release and nitrification rate at different anaerobic phase durations (< 5 kg COD/m³/d)

<table>
<thead>
<tr>
<th>duration of the anaerobic phase (h)</th>
<th>total PO₄-P released (g / m³ bed)</th>
<th>average nitrification rate (kg NH₄-N/m³ bed/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>53</td>
<td>0.9 ± 0.1</td>
</tr>
<tr>
<td>6</td>
<td>79</td>
<td>0.8 ± 0.15</td>
</tr>
<tr>
<td>8</td>
<td>97</td>
<td>0.65 ± 0.1</td>
</tr>
<tr>
<td>12</td>
<td>140</td>
<td>0.35 ± 0.05</td>
</tr>
</tbody>
</table>

Table 3. Influence of organic load on P release at different anaerobic phase durations

<table>
<thead>
<tr>
<th>duration of the anaerobic phase (h)</th>
<th>organic loading rate (kg COD/m³ bed/d)</th>
<th>total organic weight applied (kg COD/ m³ bed)</th>
<th>total PO₄-P released (g / m³ bed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>13</td>
<td>52</td>
<td>117</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>48</td>
<td>137</td>
</tr>
</tbody>
</table>

- The increase of the anaerobic contact time does not have the same effect on the fixed film reactor as on the activated sludge systems. In the latter it acts simultaneously on the biomass and the bulk liquid, enabling the
Biological phosphorus removal

production of easily biodegradable substrate (specially VFAs) in the anaerobic reactor by the fermentative heterotrophic bacteria. In the fixed film reactor the duration of the anaerobic phase acts essentially upon the fixed biomass, since its residence time and the hydraulic retention time in the reactor are completely independent. This enables an optimization of P release by controlling the time the biomass is exposed to anaerobic conditions, but, also, makes the reactor dependent of the quality of the influent, specially with regards to VFA levels.

- In a fixed film reactor it is perfectly viable to have nitrification and phosphorus removal without the need for denitrification in the system. This possibility would be particularly interesting in the coastal regions where the discharge of nitrate to the sea does not constitute a serious problem.

Total C, N and P removal - III part

In this part of the work the association of several biofilters is being studied. The objective is to reduce the proportion of anaerobic phases in the system (in the second phase = 1 filter in 2). The results being obtained at present indicate that it is possible to reduce this proportion to 20 or 25% of the total number of filters. That is to operate the system with one filter under anaerobiosis and 4 or 5 filters under aerobicism. The incorporation into the system of denitrification is also under study. The use of a new type of biofilter, having in one same unit an anoxic and an aerated zone, enables the use of the operational procedure described in the second part of this study.

CONCLUSIONS

The use of aerated biofilters technology, leading to compact and highly efficient nutrient removing treatment plants, can be extended to biological phosphorus removal. The present work confirms the viability of biological phosphorus removal in a fixed biofilm reactor operated under continuous feed conditions. The tests carried out on biological aerated filters on laboratory scale showed that two biofilters operated in series carry out complete nitrification and remove 80% of the phosphorus with a maximum hydraulic retention time of 5 hours. The hydraulic retention time and the residence time of the biomass in the reactor are independent and, therefore, the time the bacteria are exposed to alternate A/O conditions can be optimized.

The very low concentrations of suspended solids in the effluent of the biofilter enable residual levels below 1 mg PO₄-P/l to be obtained. The studies currently being carried out aim at developing a process involving also denitrification in the system.

REFERENCES


