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BIOLOGICAL PHOSPHORUS REMOVAL IN A SEQUENCING BATCH MOVING BED BIOFILM REACTOR

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ABSTRACT

Experiments have been carried out with biological phosphorus removal in a sequencing batch moving bed biofilm reactor (SBMBBR) with a plastic biofilm carrier (Kaldnes) suspended in the wastewater. The aim of the research leading to this paper was to evaluate biological phosphorus removal in this type of biofilm process. Biological phosphorus removal can be achieved in a moving bed biofilm reactor operated as a sequencing batch reactor. In order to achieve good and stable phosphorus removal over time, the length of the anaerobic period should be tuned to achieve near complete removal of easily biodegradable COD in the anaerobic period. The total COD-loading rate must at the same time be kept high enough to achieve a net growth of biomass in the reactor. Use of multivariate models based on UV-absorption spectra and measurements of the redox potential show potential for control of such a process. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Biofilm; biological phosphorus removal; moving bed; sequencing batch reactor; wastewater.

INTRODUCTION

Biological phosphorus removal (bio-P) is an alternative to chemical precipitation for removal of phosphorus from wastewater, which has a potential for reduced sludge production. Traditionally bio-P processes have been based on activated sludge and there are several process configurations in use today. However, in an activated sludge process, efficient removal of phosphorus will depend heavily on effective separation of biomass in the clarifier and on avoiding secondary release of phosphorus from the sludge in the clarifiers. In a biofilm process the concentration of suspended solids in the influent to the clarifiers is much lower than in an activated sludge process. This is an advantage with respect to the problems stated above. A biofilm process will in general be a more compact process as well, with a smaller footprint than an activated sludge process. Biological phosphorus removal depends on exposing the biomass to alternating anaerobic and aerobic conditions. In an activated sludge process this is done by circulation of the biomass through different zones in the plant. In a biofilm process this must be done by alternating between anaerobic and aerobic conditions in the same reactor.

Most of the research on bio-P has been conducted with activated sludge systems. However, there are reports of bio-P in laboratory or pilot scale biofilm processes were fixed bed reactors have been operated in a sequencing batch mode or as a continuos process with several reactors in series (Gonzales-Martinez and

Wilderer, 1991; Goncalves and Rogalla, 1992; Kerrn-Jespersen *et al.*, 1994; Goncalves *et al.*, 1994; Garzón-Zúñiga and González-Martínez, 1996). Shin and Park reported bio-P in a laboratory scale sequencing batch reactor (SBR) with a porous biomass carrier (Shin and Park, 1991)

In this work we have used a sequencing batch moving bed biofilm reactor (SBMBBR) with a plastic biofilm carrier (Kaldnes) suspended in the wastewater (Ødegaard *et al.*, 1994). The aim of the research leading to this paper was to evaluate biological phosphorus removal in this type of biofilm process.

BIO-P IN A MOVING BED BIOFILM PROCESS

Biological phosphorus removal is performed by bacteria that have the ability to accumulate more phosphate than is required for growth. The biochemical mechanisms involved in bio-P are still not known in complete detail. However, it is widely accepted that the phosphate accumulating organisms (PAO) depend not only on external substrate in the wastewater, but also on compounds stored inside the PAO. The storage products are polyphosphate (poly-P), poly-β-hydroxy-alkanoates (PHA) and in some of the models also glycogen. Our discussion is based on a biochemical model developed by Smolders which includes all three storage products (Smolders *et al.*, 1994a, b).

In the anaerobic phase of the process polyphosphate is hydrolysed and released into the wastewater providing energy for uptake of substrate. The preferred substrate is volatile fatty acids (VFA) which are used to produce PHA. Glycogen is also consumed during the anaerobic phase as a source of reducing power for the formation of PHA. In the following aerobic phase PHA is used as an internal substrate for growth uptake of phosphate, which is stored as poly-P and formation of glycogen. In an activated sludge process the fractions of poly-P, PHA and glycogen in the biomass depend on the solids retention time (SRT). In general the fraction of poly-P decreases with shorter solids retention time, while the fractions of PHA and glycogen decrease with increasing SRT (Smolders *et al.*, 1995).

In a moving bed biofilm process the solids retention time is governed by sloughing of biomass. At steady state, with a constant biomass concentration, the SRT will correlate with the loading rate of the process. In a sequencing batch reactor used for bio-P one may define several loading rates referring to the anaerobic phase, the aerobic phase and the total cycle. To avoid competition from non-phosphate accumulating aerobic heterotrophs, all influent COD should be taken up by PAO in the anaerobic phase. This implies that even at the maximum anaerobic COD-loading rate, one may have a low total COD-loading rate on the process. One may therefore expect the phosphate uptake to be controlled by the availability of PHA in the aerobic phase. Due to the low total COD-loading rate one will also get nitrification in such a process, and to ensure complete nitrification, the aerobic phase must be long enough to allow this. One has, therefore, a situation with conflicting interests. On one hand the anaerobic COD-loading rate should be kept low enough to avoid competition from non-phosphate accumulating aerobic heterotrophs, and on the other hand the total COD-loading rate should be high enough to give sufficient PHA for phosphate uptake and a net growth of biomass. One strategy for achieving this could be to operate with a relatively short total cycle length in order to have a high enough total COD-loading rate and use a relatively long anaerobic phase to minimise the competition from aerobic heterotrophs. However, one must at the same time keep the aerobic ammonium load low enough to achieve complete nitrification. The minimum length of the aerobic phase may therefore be controlled by the nitrification.

Due to the need for balancing the different loading rates and to variations in the influent concentrations of P and COD one should ideally be able to control the length of the anaerobic and aerobic phases based on on-line measurements of phosphorus and COD. Such measurements should ideally give real time, continuous profiles of COD and phosphate. Today on-line analysers for phosphate and COD/TOC, based on automation of wet chemistry analyses, are commercially available. However, due to the necessary reaction time in the analyser they have only a limited resolution in time, or a time delay depending on the type of analyser. An alternative to wet chemistry analysers may be to calculate phosphate and COD by use of multivariate modelling techniques where the inputs are measurements of UV-absorption spectra and ORP. Such a method will give considerably shorter response times than wet chemistry analyses and may also be more cost effective, especially when several parameters are to be analysed.

METHODS

The studies were carried out in a laboratory scale SBR (10 l water volume, 53% filling of KMT-media) with a constructed wastewater. A schematic representation of the laboratory apparatus is shown in Figure 1. Acetate was used as carbon source and a phosphate buffer was used as P-source. The total loading rates of acetate measured as COD and phosphorus were varied in the range 0.3 to 1.2 kg COD/m^3*d and 0.012 to 0.131 kg PO_4-P/m^3*d respectively. The wastewater also contained ammonium (25 mg NH_4-N/l) corresponding to an aerobic loading rate in the range of 0.06 to 0.27 kg NH_4-N/m^3*d. The pH was controlled at 7.5 by addition of HCl (0.5 M) or NaOH (0.5 M). The headspace of the reactor was flushed with nitrogen gas to ensure anaerobic conditions in the anaerobic phase of the cycle.

The SBR was operated with a total cycle length of 4 to 6 hours and varying lengths of the anaerobic period. Dissolved oxygen concentration (DO), redox potential (ORP) and pH were measured on-line and recorded by a data logger. The water volume in the reactor was emptied completely between each cycle.

UV-absorption spectra were measured on filtered samples and used together with on-line measurements in a multivariate model for phosphate, COD and nitrate.

All wastewater analyses were performed according to Norwegian Standard.

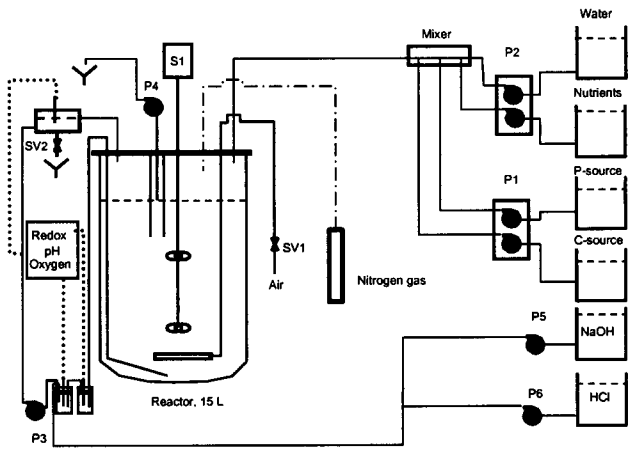

Figure 1. Laboratory SBR.

RESULTS AND DISCUSSION

The phosphate removal efficiency depended heavily on the operating conditions. Removal efficiencies up to 98% were achieved. Plots of phosphate removal versus the total phosphate-loading rate showed no clear trends, which is as expected if influent phosphate concentration is not a controlling factor. However, the aerobic phosphate removal rate showed a strong correlation to the anaerobic phosphate release rate, Figure 2A. Since production of PHA necessary for phosphate uptake is linked to phosphate release, these results were as expected. However, it is not the anaerobic phosphate release rate but the amount of PHA formed which is most important. A better measure of this can be found from the difference in phosphate concentration at the beginning and end of the anaerobic phase. In Figure 2B a plot of the aerobic phosphate removal rate versus the calculated aerobic PHA loading rate is shown. The aerobic PHA loading rate was calculated with a ratio between phosphorus released to PHA produced of 0.32 mg PO_4-P/mg COD (Smolders *et al.*, 1994a; Christensson, 1997).

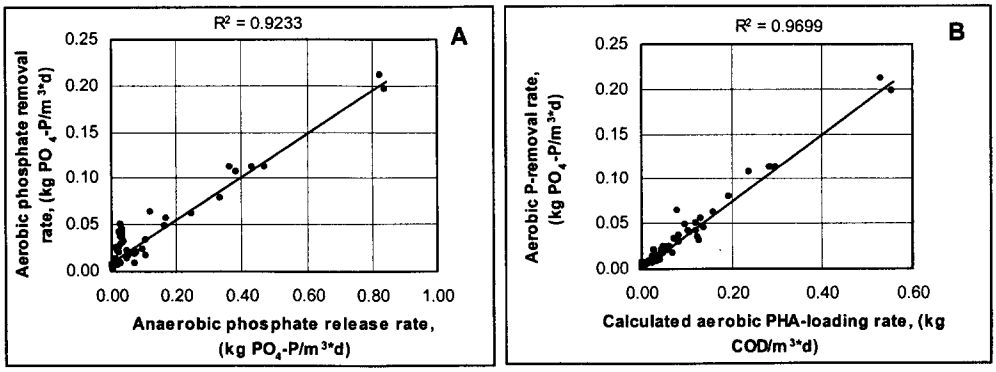

Figure 2. Aerobic phosphate removal rate versus anaerobic phosphate release rate (A) and calculated aerobic PHA loading rate (B).

The results support the theoretical discussion presented above, concluding that phosphate removal rate will be controlled by the availability of PHA. The majority of the results show phosphate removal rates below 0.1 kg PO_4-P removed per m^3 reactor volume and day. However, even at the highest removal rates obtained, the results show good correlation to the PHA loading rate, indicating that availability of PHA will always be the controlling factor for the phosphate uptake in the KMT moving bed process.

Another factor of importance may be competition between PAO and other heterotrophs. In Figure 3 a plot of the aerobic phosphate removal rate versus the aerobic phosphate-loading rate is shown for different total COD-loading rates.

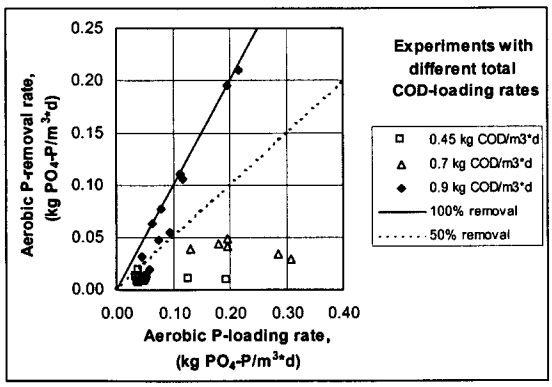

Figure 3. Aerobic phosphate removal rate versus aerobic phosphate loading rate at different total COD-loading rates.

The results show good phosphate removal at the highest total loading rate of COD. However, some of the results at this COD-loading rate show a removal of phosphate of only 50%. In these experiments the anaerobic COD removal was low (average 60%) while the average anaerobic COD removal in the experiments with good phosphorus removal was 84%. We believe that the reason for the difference in phosphorus removal was competition from non-phosphate accumulating aerobic heterotrophs. If the anaerobic period is shorter than necessary for consumption of all influent COD, the fraction of bio-P bacteria in the biofilm may decrease due to growth of non bio-P heterotrophs in the aerobic period. This in turn will lead to a poor removal efficiency of phosphate.

In the experiments with a total loading rate of COD of 0.45 kg COD/m^3*d, the phosphate removal rate was too low to achieve a net growth of biomass due to a too low total loading rate of COD. Consequently the

removal of phosphate was poor. In the experiments with a total loading rate of COD of 0.7 kg COD/m^3*d, the total cycle length was decreased from 6 hour to 4 hours and the anaerobic phase was increased from 1 hour to 2 hours. The increase in the total loading rate of COD and reduction of the anaerobic COD loading rate, resulted in an increase in phosphate removal. However, sufficient phosphate removal was not achieved. The reason for this was probably the short length of the aerobic phase (1.7 hours).

In Figure 4 typical profiles of the phosphate concentration (A) and soluble COD concentration (B) during the cycle are shown for the experiments with a total cycle length of 6 hours and an anaerobic phase of 1 hour.

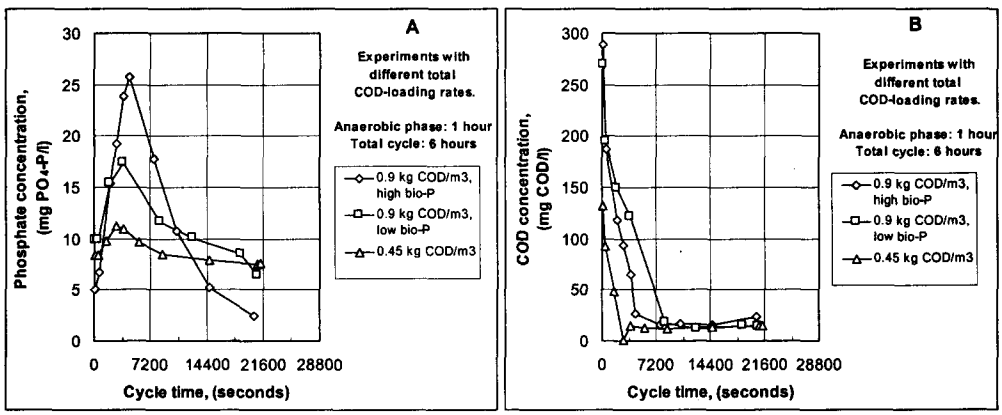

Figure 4. Typical concentration profiles in SBR-cycles with 1 hour anaerobic phase and a total cycle length of 6 hours, A: Phosphate, B: COD

The results show that in the experiments with a total COD-loading rate of 0.9 kg COD/m^3*d and low P-removal, the removal of COD in the anaerobic phase was low and also less phosphate was released in the anaerobic phase than in the experiments with good P-removal. In the experiments with 0.45 kg COD/m^3*d all COD was removed in the anaerobic phase so competition from non-PAO in the aerobic phase should not be a problem. However, as stated earlier, the total COD-loading rate was probably too low to give sufficient net growth of biomass in order to achieve a good phosphate removal.

The short aerobic phase in the experiments with a total COD-loading rate of 0.7 kg COD/m^3*d gave a high aerobic ammonium loading rate and resulted in incomplete nitrification with formation of nitrite, which may inhibit the bio-P activity (Christensson, 1996). It is possible that inhibition by nitrite caused the low phosphate removal rates, but the length of the aerobic phase may also have been too short for sufficient uptake of phosphate.

The removal of ammonium at different aerobic loading rates of ammonium is shown in Figure 5A and the aerobic nitrogen removal rate is shown in Figure 5B for different aerobic nitrogen loading rates. The results in Figure 5A show that one should operate at an aerobic ammonium loading rate below about 0.2 kg NH_4-N/m^3*d in order to achieve an ammonium removal efficiency of about 95%. The results with the lower removal efficiencies at low loading rates were from experiments with excess COD after the anaerobic period. In our experimental set-up an aerobic ammonium loading rate of 0.2 kg NH_4-N/m^3*d corresponds to an aerobic phase of 2.5 hours, which is longer than used in the experiments with a total COD-loading rate of 0.7 kg COD/m^3*d.

In an anaerobic–aerobic process with no nitrate in the anaerobic phase one would normally expect the removal of ammonium to be caused by growth and nitrification. However, in our experiments we observed higher net nitrogen removal rates than can be explained by growth in some experiments. This is shown in Figure 5B, where nitrogen removal rates corresponding to a removal efficiency of 70%–80% were observed in experiments with a total COD-loading rate of 0.9 kg COD/m^3*d when the phosphate removal was good.

In these experiments, a nitrogen removal efficiency of up to 40% can be explained by growth. In the experiments with a total COD-loading rate of 0.9 kg COD/m^3*d and a poor phosphate removal, the net nitrogen removal was lower, at about 30%-40%, and can be explained by growth. In the experiments with total COD-loading rates of 0.70 and 0.45 kg COD/m^3*d the net nitrogen removal varied more, but was up to about 20%-35%. In these experiments the amount of COD fed to the reactor was half the amount of COD fed to the reactor in the experiments with a total COD-loading rate of 0.9 kg COD/m^3*d, while the amount of ammonium was the same. In these experiments a nitrogen removal efficiency of up to 20% can therefore be explained by growth.

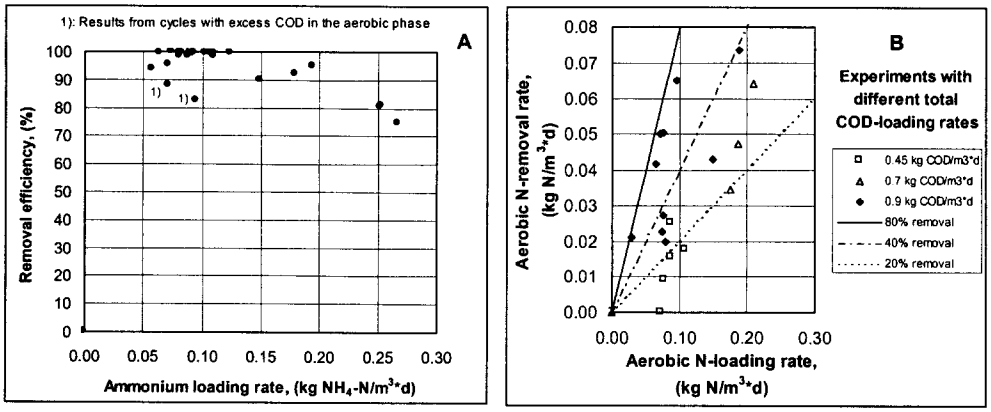

Figure 5. Removal efficiency of ammonium at different aerobic ammonium loading rates (A), and aerobic nitrogen removal rate (B).

Since the only nitrogen fed to the system was ammonium, the results indicate simultaneous nitrification and denitrification in the aerobic phase in the experiments with good phosphate removal, and in some of the experiments with a total COD-loading rate of 0.7 kg COD/m^3*d. The DO concentration reached 2 mg O/l shortly after start of aeration, and oxygen was therefore available as electron acceptor in the aerobic phase. However, it has been proposed that simultaneous nitrification and denitrification can take place in a layered biofilm where the deeper layers are anoxic (Garzón-Zúñiga and González-Martínez, 1996).

Since the COD was removed in the anaerobic phase where there was no nitrate, it is possible that phosphate removal was performed by bacteria using nitrate as electron acceptor. However, the ratio of COD removed to nitrogen removed and the ratio of nitrogen removed to phosphorus removed were higher than expected according to the model for denitrifying phosphorus-removing bacteria (DPB) reported by Kuba (Kuba *et al.*, 1996). Another explanation may be that denitrifying bacteria capable of storing COD in the anaerobic phase were present. We have not seen this reported, but van Loosdrecht proposed that storage polymers might play an important role under conditions were the availability of substrate varies greatly (van Loosdrecht *et al.* 1996).

Multivariate models

The concentrations of phosphate, soluble COD and nitrate throughout the cycle were modelled by use of a chemometric modelling technique called partial least squares regression (Martens and Næs, 1994), with UV-spectra in the range 190-250 nm and the on-line measurement of ORP as raw data. The correlation between predicted and measured concentrations of phosphate, nitrate and soluble COD are shown in Figure 6A, B and C, respectively. The correlation between predicted and measured values for nitrate and COD were quite good, but the results with respect to phosphate showed greater variations.

In order to be used for process control the models should be able to determine the concentration levels in the influent. For example the ratio of COD to P in the influent may be used as a criteria for dosage of additional C-source. The models should also be able to follow changes in the concentrations during the cycle, and in

this respect relative changes in concentration may be more important than absolute values. For example the length of the anaerobic phase could be controlled by criteria such as: aeration should not start until the uptake rate of soluble COD or the phosphate release rate fall below a given low value. The end of a cycle could be controlled in a similar manner by criteria for a minimum phosphate uptake rate.

The models need to be validated in experiments with real wastewater. However, the results are promising and show the potential for this type of models in control of such a process.

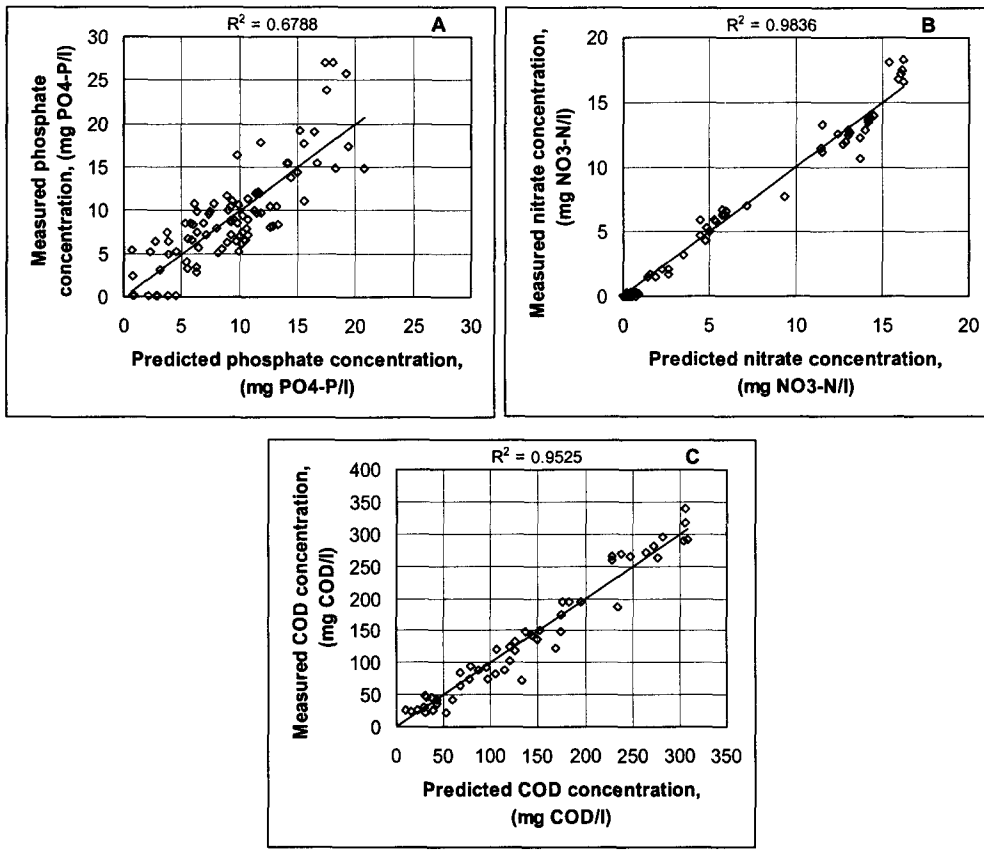

Figure 6. Correlation between predicted and measured concentrations of phosphate (A), nitrate (B) and soluble COD (C).

CONCLUSIONS

Biological phosphorus removal can be achieved in a moving bed biofilm reactor operated as a SBR. In order to achieve good and stable phosphorus removal over time, the length of the anaerobic period should be tuned to achieve near complete removal of easily biodegradable COD in the anaerobic period. The total COD-loading rate must at the same time be kept high enough to achieve a net growth of biomass in the reactor.

Use of multivariate models based on UV-absorption spectra and ORP measurements show potential for control of such a process. However, the models need to be validated in experiments with real wastewater.

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