Nutrient-limited biofilm pretreatment: an efficient way to upgrade activated sludge plants

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ABSTRACT: We studied biological treatment of bleached kraft mill effluent in a nutrient (phosphorus) limited moving bed biofilm process followed by an activated sludge process on a pilot plant scale. Operating the process under phosphorus limitation with an influent BOD_7:N:P-ratio of 400:10:1 did not compromise organic removal and resulted in excellent sludge settleability and reduced sludge production. At hydraulic retention times of 2.4-3 h in the biofilm process and 6.8-8 h in the activated sludge plant, the nutrient-limited biofilm/activated sludge system removed 98% of BOD_7 and 70%-80% of COD. The sludge volume index was 40-120 mL/g and the effluent TSS was around 20 mg/L. The biosludge yield was as low as 0.09 kg TSS/kg COD removed (0.17 kg TSS/kg BOD removed). Due to nutrient limitation, we could achieve low discharge levels of nutrients (around 0.3 mg/L of total P and 4 mg/L of total N). EDTA was degraded by 95% in the process.

Because of nutrient (phosphorus) limitation, the biomass produced in the biofilm process became slimy. The excess sludge from the biofilm process rapidly degraded in the subsequent activated sludge plant, explaining the low overall sludge yield in the process. Large compact flocs without any slime content dominated the activated sludge. The results of the study indicate nutrient-limited biofilm pretreatment can efficiently decrease the sludge yield and secure good sludge settling characteristics in activated sludge plants.

Application: By applying the principles described in the paper, mills may improve their effluent treatment considerably.

The activated sludge process is one of the most commonly used systems for biological treatment of pulp and paper industry effluents. The effluent to be treated is fed to one or more aeration basins, in which bacteria and other microorganisms—the activated sludge—are used to convert organic matter in the effluent to carbon dioxide, water, and new microbial biomass. The mixture of treated effluent and activated sludge goes to a clarifier, in which the sludge is separated from the effluent by settling. Most of the sludge is returned to the aeration basin to maintain a high concentration of active microorganisms in the system, while a minor part, corresponding to the sludge production in the process, is taken out to be wasted. The separation of sludge from water depends on the microorganisms growing in large aggregates, flocs, since individual microorganisms are too small to settle. Unfortunately, the microorganisms do not always grow in the desired way, leading to sludge separability problems such as dispersed growth, pin-point flocs, sludge bulking (excessive growth of filamentous bacteria) and slime formation [1]. This may result in decreased treatment performance, since biomass escaping from the clarification process means increased discharge of total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_7) and nutrients such as nitrogen and phosphorus. Furthermore, loss of active biomass from the process leads to a decreased treatment capacity. Consequently, it is of crucial importance to secure the growth of biomass with good settling characteristics in the activated sludge process.

Deficiency in oxygen or nutrients may cause poor sludge separability. Low oxygen may cause sludge bulking through growth of filamentous bacteria such as *Sphaerotilus natans* [1], while nutrient deficiency may cause filamentous bulking as well as an overproduction of slime (polysaccharides) [2]. Even at oxygen and nutrient sufficient conditions, sludge bulking frequently occurs due to the growth of so-called low F/M (food to microorganism) filamentous organisms, i.e. filamentous bacteria favored by low levels of biodegradable organics in the aeration basin [1]. To avoid this problem, activated sludge processes are often designed for plug-flow or with selectors (initial highly loaded compartments), measures that suppress many low F/M filaments [1, 3]. Selectors can be operated with or without aeration and have been successful at controlling filament growth for various pulp and paper industry effluents [3]. However, selectors have failed to control sludge bulking and they are not effective at controlling filamentous growth caused by nutrient limitation [3]. Consequently, a careful dosage of nutrients in some excess is required to maintain good settleability of the sludge in selector/activated sludge systems. The generally recommended nutrient needs for activated sludge corresponds to a BOD_7:nitrogen (N):phosphorous (P) ratio in the influent to biological treatment of 100:5:1 [2, 4]. Different nutrient control strategies have been suggested to supply sufficient amounts of nutrients while at the same time avoiding overdosing [4].

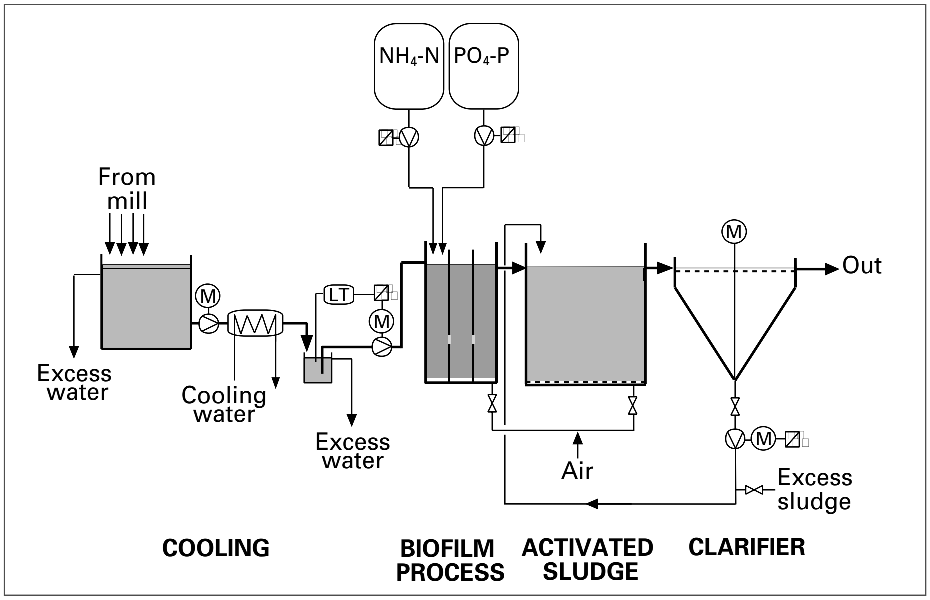
Pretreating the effluent in a high rate biofilm process, thereby removing the readily biodegradable organic matter before activated sludge treatment, is an alternative way of controlling filamentous growth in activated sludge plants. Traditionally, trickling filters have performed such pretreatment. In recent years the moving bed biofilm reactor (MBBR) has largely taken over this role, and in some cases complemented or replaced existing trickling filters that have suffered from overload, clogging problems, or odor formation [5-7]. Biofilm pretreatment generally suppresses filament growth in the subsequent activated sludge process effectively, resulting in a low sludge volume index

[7, 8]. Nutrient requirements for sequential biofilm/activated sludge treatment are generally the same as the requirements in pure activated sludge plants, the operating strategy being to maintain some excess in soluble available nutrients in both biofilm and activated sludge reactors. However, recent unpublished studies show great advantages with operating sequential MBBR/activated sludge treatment (biofilm/activated sludge, BAS) under strict nutrient limitation in the MBBR. Operating the BAS process on different kraft mill effluents, with influent BOD_7:N:P ratios of 400:10:1, or even lower nutrients, yields very good activated sludge settling characteristics and a dramatically decreased biosludge production, without compromising organic removals. This is in great contrast to general experiences with activated sludge plants operated at such low nutrient levels. For such plants, you would expect very poor sludge characteristics due to filamentous growth or slime formation (polysaccharide overproduction) [2].

Microscope investigations of the biomass in the different stages of the nutrient-limited BAS process have revealed the production of a very slimy sludge in the biofilm process, but only traces of this sludge in the activated sludge process. Despite continuous feeding of the excess sludge from the biofilm process to the activated sludge plant, the latter is dominated by very compact and well settling flocs. Obviously, the microbial conversions in the process include polysaccharide overproduction from soluble organic matter in the biofilm stage, and degradation of those polysaccharides in the subsequent activated sludge plant. In this way, we eliminate a great part of the readily biodegradable organic matter in the effluent in a two-step conversion, decreasing sludge production and leaving little biomass produced from the readily biodegradable organic fraction in the process. This paper presents results from pilot plant trials with the nutrient-limited BAS process on bleached kraft mill effluent. The aim of the study was to confirm results previously achieved in laboratory scale.

THE MÖRRUM MILL

We conducted the pilot plant trial at the Södra Cell Mörrom mill located along Sweden's southern coast. The mill has a capacity of 425,000 metric tons/year of totally chlorine free (TCF) and elemental chlorine free (ECF) bleached kraft pulp. The pulp is produced in two lines, the products being fully bleached (TCF) hardwood pulp, fully bleached (ECF-light) softwood pulp, and partially bleached (TCF) softwood pulp. We conducted the pilot trial on bleach plant effluent from the mill, which is generated in an amount of approximately 36,000 m^3/day.



1. The biofilm/activated sludge pilot plant.

PILOT PLANT

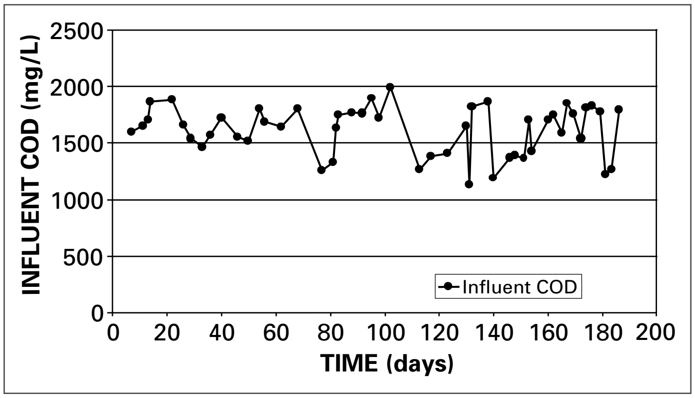
The pilot plant (**Fig. 1**) used for the trials is comprised of an aerated biofilm process with a total volume of 900 L, which could be divided into two or three compartments by movable separating walls, followed by an aerated 2 m^3 activated sludge tank and a clarifier. During the first part of the trials, until day 124, we used a conical clarifier without scraper and with a surface area of 2 m^2. On day 124, we switched to a cylindrical clarifier, with a surface area of 0.6 m^2 and equipped with a sludge scraper. A screw pump returned sludge from the bottom of the clarifier to the activated sludge tank throughout the experiment at a flow equal to the influent flow to the process. The biofilm stage was filled to 50% of the bulk volume with suspended carrier media of the type Natrix O (Kaldnes Miljøteknologi AS, Norway).

The bleach plant effluent was cooled to about 38°C in a heat exchanger and pumped by an impeller pump to the first biofilm compartment. All tanks were aerated by means of a blower and coarse bubble bottom aerators. Membrane pumps sent nutrients, in the form of diluted ammonium sulfate and phosphoric acid, to the first biofilm compartment. When needed, excess sludge from the activated sludge plant was wasted manually to keep the sludge concentration in the process below 5 g/L.

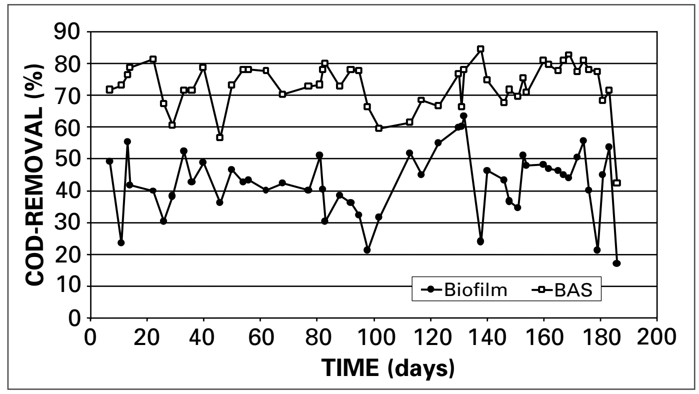
EXPERIMENTAL

The trials included an experimental phase and a verification phase. In the first phase, we tried different hydraulic retention times and nutrient dosages. In the second phase, we made fine adjustments and determined the results when using the final configuration.

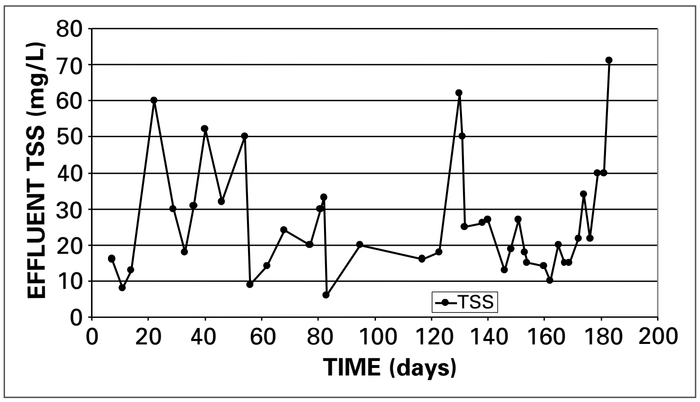
Analyses of COD, total N, total P, ammonium as nitrogen (NH_4N), and orthophosphate as phosphorous (PO_4P) were carried out using Dr. Lange methods LCK 114, LCK 238, LCK 349, LCK 304, and LCK 349, respectively. We analyzed TSS according to Standard Methods [9]. We analyzed BOD according to Swedish Standards [10] and EDTA by high-performance liquid chromatography (HPLC). COD and TSS were determined 5 days per week, while nutrient analyses were carried out 2-4 times per week. We measured BOD 5 times during the trial and analyzed EDTA 15 times. We examined the biomass in the biofilm and activated sludge reactors by phase contrast and interference contrast microscopy 1-2 times per week.



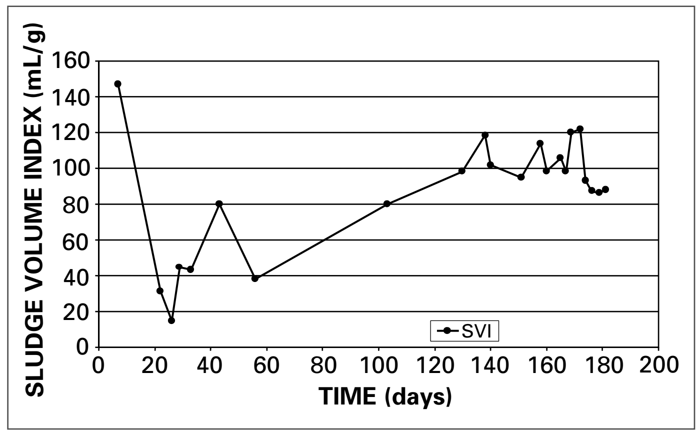
2. Influent COD to the BAS pilot plant.



3. COD-removal over the biofilm stage (filtered) and the whole BAS process.



4. TSS in the effluent from the BAS pilot plant.



5. Sludge concentration in the aeration basin of the BAS pilot plant.

We started the process at a flow of 250 L/h, using two 300-L sections in the biofilm tank. This resulted in a hydraulic retention time (HRT) of 2x1.2 h in the biofilm process and 8 h in the activated sludge plant. We inoculated the activated sludge process with 100 L of activated sludge from a nearby pulp and paper mill and started the biofilm process without inoculation.

On day 99, we modified the biofilm process into a two-stage process with a volume of 300 L in the first compartment and 600 L in the second. At the same time, we increased the feed flow to 300 L/h, resulting in a process with HRTs of 1+2 h in the biofilm process and 6.7 h in the activated sludge process.

On day 139, we introduced a separating wall in the biofilm process. That resulted in a three-stage biofilm process with an HRT of 3x1 h, followed by an activated sludge plant with an HRT of 6.7 h. At the same time, we moved the sludge return to the third biofilm stage. The process operated in this configuration until day 152, when the sludge return was moved back to the aeration basin. The We started the verification phase on day 168, continuing until day 177. We then increased the feed flow to 400 L/h, resulting in an HRT of 3x0.75 h in the biofilm process and 5 h in the activated sludge plant. On day 180, we moved the sludge return to the second biofilm stage. The trial ended on day 187.

RESULTS

COD-removal and general observations

The influent COD varied between 1200 and 1700 mg/L through most of the experiment (**Fig. 2**). The process operated initially with excess nutrients (BOD_7:N:P approximately 100:5:1). We allowed it to stabilize during the first month. Shortly after start up, we obtained filtered COD removals of 40%-50% over the biofilm process and 70%-80% over the whole process (**Fig. 3**). During month 2 and 3, we decreased the phosphorus dosage successively to turn the process into a nutrient-limited BAS. From day 70, the process operated with an influent BOD_7:P-ratio around 400:1. This forced the COD removal over the biofilm part down to a relatively constant level of about 40%, while the removal over the whole process remained unchanged (Fig. 3). In general, the process worked very well at the reduced phosphorus dosage. The sludge separability properties were excellent, with an effluent TSS around 20 mg/L (**Fig. 4**) and a sludge volume index of about 40 mL/g TSS (**Fig. 5**). BOD_7 removal was about 98% and the EDTA removal around 95%. Nitrogen was maintained in excess during this period.

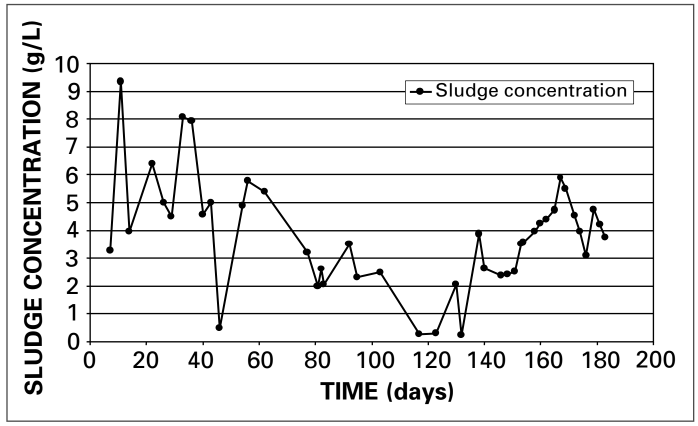
On day 96, the phosphorus dosage was stopped completely, resulting in a BOD_7:P-ratio of approximately 600:1. This proved to be too drastic. The COD-removal over the biofilm process decreased rapidly and the removal over the whole process decreased down to 60% (Fig. 3). At the same time, we encountered problems with the clarification. The activated sludge repeatedly stuck to the walls of the conical clarifier, resulting in very low sludge concentrations in the aeration basin. These mechanical problems continued until the clarifier was exchanged for a new, cylindrical unit with a scraper on day 124, after which the sludge concentration could easily be built up again (**Fig. 6**). We increased the phosphorus dosage to speed up sludge growth. The COD removal in the biofilm process (which was operated at a total HRT of 3 h since day 99) quickly increased to 55%-60%, while the removal over the whole BAS process reached approximately 75% (Fig. 3).

On day 139, we reconfigured the biofilm process into a three stage plant, and moved the sludge return to the last biofilm reactor. As there was a certain contact between the three biofilm stages, a significant amount of activated sludge was leaking back to the first two stages and the process approached a selector/activated sludge process. The COD removal over the biofilm reactors became somewhat lower during this period with sludge recycling than before, approximately 40%. We considered diluting the soluble COD with the recycled sludge stream when calculating the removal over the biofilm process. The decrease in removal was most likely caused by the HRT in the biofilm process in practice decreasing considerably due to the dilution with recycled sludge (the influent was diluted with a stream of equal size, containing inert soluble COD only). The COD removal over the whole BAS process was around 70% during the period with sludge recycling (Fig. 3).

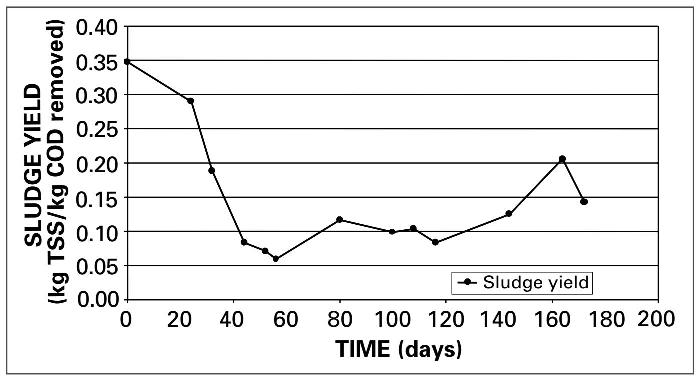
After moving the sludge return back to the aeration basin on day 152, we again decreased the phosphorus dosage to give a BOD_7:P-ratio of 400:1 and decreased the nitrogen dosage to a BOD_7:N-ratio of 40:1. The COD removal over the biofilm process remained between 45% and 50%. The removal over the whole process stabilized at about 80%, where it remained throughout the day 168-177 verification phase (Fig. 3). The increase in feed flow on day 177 caused a quick drop in COD reduction in the biofilm process to about 20%, while the removal over the whole BAS process remained at close to 80%. We did not attempt to acclimate the process to this loading. Instead, we moved the sludge return to the second biofilm reactor. The COD reduction in the biofilm process recovered under these conditions and reached 50%, with a 70% removal over the whole process. However, the sludge separability properties deteriorated during the short period with sludge return to the biofilm process. After four days of this operation, the effluent TSS had increased to 70 mg/L and the trial ended.

Sludge separability and effluent TSS

With few exceptions, the effluent TSS was below 30 mg/L during the experiment (Fig. 4). The average effluent TSS was below 20 mg/L for periods when we operated the BAS process under strict phosphorus limitation, which is well in agreement with previous experiences. The sludge separability properties were good, except during the last week when we recycled sludge to the second biofilm stage. The sludge volume index (SVI) was around 40 mL/g during the first period of nutrient limitation, which must be considered very low (Fig. 5). The SVI increased to around 100 mL/g during the later part of the experiment, which is still good. After increasing the load on day 177, the sludge separability deteriorated. We only operated the process for three days as a pure BAS process at this load. The results clearly indicated, however, that the activated sludge process lacked the capacity to remove free-swimming bacteria entering from the biofilm process at this load. This resulted in an increased effluent TSS to 40 mg/L. The amount of free-swimming bacteria decreased when the sludge return was moved to the second biofilm reactor, but high amounts of pin-point flocs arose instead and the effluent TSS increased rapidly to 70 mg/L.



6. Sludge volume index of the activated sludge in the BAS pilot plant.



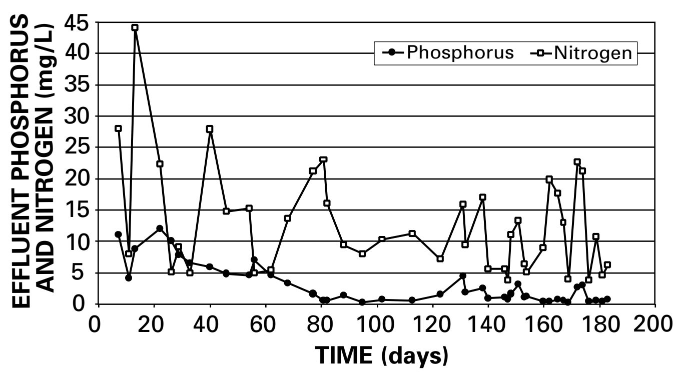
7. Net sludge yield over the whole BAS process during the last part of the pilot trial.

BOD and EDTA removal

We measured BOD and EDTA on only a few occasions, but the results clearly showed high removals, around 98% and 95%, respectively, during the periods of nutrient limitation. The influent BOD_7 varied between 520 and 700 mg/L, while the treated effluent BOD_7 was in the range of <8-12 mg/L. The influent level of EDTA was approximately 60 mg/L. In conjunction with the mechanical separation problems starting day 96, EDTA degradation was lost. This was most likely due to the dramatically decreased sludge age in the system, resulting from the low sludge concentration. However, the removal was regained when the sludge concentration had been built up again. The pH in the activated sludge process was well above 8 during the first part of the trial, which favors EDTA degradation. During the later part of the trial, the pH was often lower than acceptable for maintaining a stable EDTA degradation. However, we obtained a high removal—approximately 95%—during the verification phase when the pH was between 7.5 and 8.

Sludge yield

We determined the net sludge yield in the BAS process on a few occasions during the first period of nutrient limitation, showing values between 0.05 and 0.10 kg TSS/kg COD removed (approximately 0.09-0.19 kg TSS/kg BOD removed). Operating the process as a conventional BAS system (nutrients in excess) from day 124 to 139 resulted in a sludge yield of approximately 0.2 kg TSS/kg COD removed (0.4 kg TSS/kg BOD removed). The sludge yield increased to an average of 0.23 kg/kg COD when moving the sludge return to the biofilm process, which is



8. Total nitrogen and total phosphorus in the effluent from the BAS process.

PARAMETER	INFLUENT (mg/L)	EFFLUENT (mg/L)	REDUCTION (%)
COD	1670	350	79
TSS	64	22	66
Tot-N	10.3	3.8	63
Tot-P	1.4	0.32	77
EDTA	68	2.6	96

I. Summary of results during the verification phase.

PARAMETER	EFFLUENT NITROGEN (mg/L)	EFFLUENT PHOSPHORUS (mg/L)
Inert*	2.1	0.05
Particulate	1.4	0.19
Readily available	0.1	0.08
EDTA	0.2	–
Total	3.8	0.32

*Soluble total N or total P remaining after biological treatment, excluding the available inorganic forms NH_4N, NO_2N, NO_3N, and PO_4P.

II. Effluent nutrient concentrations during the verification phase divided into different fractions.

a normal value for activated sludge treatment of this kind of effluent. After again turning the process into a nutrient-limited BAS, we regularly determined the sludge yield (**Fig. 7**), which stabilized around an average value of 0.09 kg/kg COD (0.17 kg TSS/kg BOD removed). The increase in load and recycling of sludge to the biofilm process the last few days of the trial resulted in an increase in sludge yield to approximately 0.18 kg/kg COD removed.

The net sludge yield over the biofilm process was fairly constant at a level of approximately 0.30 kg TSS/kg soluble COD removed throughout the trial. We saw no significant difference in this yield between periods with nutrient limitation and periods with nutrients in excess.

Nutrient consumption

As phosphorus was the nutrient primarily used to limit the process, we obtained abundant data showing low effluent phosphorus concentrations after starting the limitation during month 3. When increasing the phosphorus dosage in order to rebuild the sludge concentration after the mechanical separation problems, we obtained a phosphorus discharge of 1-1.5 mg/L (**Fig. 8**). After stopping sludge return to the biofilm process and decreasing the phosphorus dosage again, an effluent phosphorus level below 0.5 mg/L was established and maintained throughout the verification phase. The higher values (3 mg/L) obtained on two occasions during this period were caused by stops in the feed due to fiber plugs in the pump, resulting in only nutrients being pumped into the process without any organic load.

We operated the process with some excess in nitrogen through most of the trial. However, during the verification phase, we reduced the nitrogen dosage to a minimal level, which resulted in low nitrogen discharge. After decreasing the nitrogen dosage to the lowest level on day 168, the total nitrogen discharge went down to around 4 mg/L (Fig. 8). Unfortunately, the operation during this short period was disturbed by fibers plugging the feed pump on two occasions, resulting in two peaks in the effluent nitrogen level. Nevertheless, the results during the verification period confirmed the level of 4 mg/L to be an expected nitrogen discharge level for the nutrient-limited BAS when keeping both phosphorus and nitrogen dosage low.

During the verification phase, 10 mg/L N and 0.4 mg/L P were dosed to the wastewater, which together with the available nutrients occurring naturally in the wastewater indicate a nutrient demand of approximately 15 mg/L N and 1.5 mg/L P. This corresponds to a BOD_7:N:P-ratio of 400:10:1, to be compared with the "rule of thumb" for biological treatment of 100:5:1.

Microbiology

We followed the microbiology of the process through phase contrast and interference contrast microscopy throughout the trial. Large compact activated sludge flocs containing high levels of rotifers and other microanimals developed rapidly in the beginning of the trial. Initially, the excess sludge from the biofilm process was characterized by small biofilm fragments and large amounts of free-swimming bacteria. This changed as we imposed nutrient limitation on the process, resulting in large slimy chunks of biomass and lower amounts of free swimmers. The activated sludge further improved under nutrient limitation and showed very compact flocs. The level of filamentous bacteria was very low, the filament index according to Jenkins [1] was 1. During the first period with nutrient limitation, we observed high amounts of worms in the sludge, indicating a very long sludge age.

When rebuilding the sludge after separation problems, the activated sludge once again developed large flocs, but this time somewhat less compact and containing fewer microanimals. The flocs turned much smaller during the period with sludge return to the third biofilm stage. When the process was changed back to a nutrient-limited BAS, the excess biofilm sludge again turned into large slimy biofilm fragments, and the activated sludge flocs grew large and compact with lots of rotifers on them. We observed higher amounts of filamentous bacteria compared with the first nutrient-limited period, which explains the higher SVI value. However, the filament level was far from any risk of sludge bulking (filament index 3) and sludge separation worked very well. The dominating filamentous bacterium was *S. natans*. After increasing the load and moving the sludge return pipe to the second biofilm reactor the last week of the trial, the floc size decreased dramatically, which caused the sharp increase in effluent TSS.

Verification phase results

Table I summarizes the results achieved with the nutrient-limited BAS process during the verification phase. We excluded the two occasions with high nutrient discharge due to stoppages because they did not represent normal operation.

Table II shows the different nutrient fractions making up the total effluent nutrient concentrations. The table shows that the effluent concentrations of available nutrients were very low. Even the rather difficult to degrade EDTA was kept at a low concentration. Most of the discharge was related to the inert and particulate fractions. Obviously the nutrient discharge was very close to what can optimally be achieved by biological treatment under undisturbed operation.

DISCUSSION

The pilot plant study confirms the results previously obtained in laboratory trials on similar effluents. The BAS type of process can be operated on bleached kraft mill effluent under strict nutrient limitation, resulting in excellent sludge separability and low sludge production. We operated the BAS plant under strict phosphorus limitation during two periods of 27 and 25 days each. We also kept nitrogen very low during the second period, the verification phase. Each period represented almost three sludge ages. The sludge quality remained very good throughout these periods and the microscope examinations revealed no tendency of deteriorated sludge separability. The treated effluent TSS increased somewhat toward the end of the verification phase, from about 15 mg/L up to about 25 mg/L. This may have been part of the normal variations or might relate to the rapid decrease in aeration basin sludge concentration at that time because of increased sludge wasting. No sludge was wasted from the process from the start of the verification phase up to day 166 when the sludge concentration had built up to above 5 g/L. Sludge was then wasted daily and the sludge concentration decreased rapidly down to 3 g/L. The considerably lower sludge level in the clarifier resulting from this increased wasting and the consequently lower "filtering" effect of the sludge in the clarifier on the treated effluent may explain the TSS increase. As stated, no changes in the sludge characters observed in the microscope gave reasons for an increased TSS discharge. Furthermore, the treatment performance, e.g. the COD removal, remained high. Therefore, we see no reason to expect that the nutrient-limited process would lose performance in the long run. Laboratory tests also have confirmed long term stable performance of the nutrient-limited BAS system.

Introducing biofilm pretreatment is a well known possibility to increase the capacity and stability of activated sludge plants considerably, without need for much additional process volume. The nutrient-limited operation of the BAS process, demonstrated in this paper, adds the advantages of further improved sludge separability, a low sludge production, and dramatically decreased nutrient requirements. The biosludge yield obtained in this study was less then half of that expected for a low rate activated sludge plant. Dewatering and disposal of excess sludge from biological treatment, as well as nutrient dosage, represent high operating costs [4, 11]. Upgrading activated sludge plants through biofilm pretreatment may not only improve treatment capacity and performance, but can also reduce operating costs significantly.

Whether the nutrient-limited BAS process can be applied for a wide variety of effluents or only certain types needs to be investigated. Pilot plant trials are being conducted on effluents from the production of sulfite pulp, TMP/paper, and board from recycled paper.

The BAS process was operated at volumetric loading rates of around 4 kg COD/m^3 d and 1.5 kg BOD_7/m^3 d. Due to the high organic conversion rate in the biofilm pretreatment, the F/M-ratio for the activated sludge process was fairly low, around 0.15 kg BOD_7/kg TSS d. As a consequence of low sludge yield, the solids retention time (SRT) in the activated sludge process was much longer (around 10 days) than for an equal size conventional activated sludge plant. This made possible the degradation of EDTA, which requires long SRTs.

The microscope studies confirmed the microbial mechanisms observed in previous experiments. Biomass with high slime (polysaccharide) content formed in the biofilm process and was later consumed in the activated sludge system. We did not measure the polysaccharide content of the sludge *per se*, but the high slime content in the biofilm biomass was clearly seen in the microscope and confirmed by reverse India ink stain, as was the absence of this type of sludge in the activated sludge process. Thus, we can explain the low sludge yield obtained in the nutrient-limited BAS process, as compared to a pure activated sludge system, by the two-stage degradation occurring in the former. In the first stage (the biofilm process), the readily biodegradable soluble organic matter is consumed. The greater portion is oxidized to carbon dioxide and water, but a significant part is converted to biomass (0.3 kg TSS/kg COD removed). This biomass acts as substrate for other microorganisms in the subsequent activated sludge process, resulting in another loss of organic matter due to oxidation. With an assumed yield factor of 0.2 kg TSS/kg TSS consumed for this conversion, the resulting yield of sludge from the readily biodegradable COD would be 0.06 kg TSS/kg COD removed (0.2x0.3). In the one stage degradation in a pure activated sludge plant, the readily biodegradable organic matter is converted to carbon dioxide, water, and biomass with a typical biomass yield around 0.25 kg TSS/kg COD removed. The key to the low sludge production in the BAS system is the biodegradability of the sludge formed in the biofilm process. In practice, the degradation of the excess biofilm sludge may not be 100%, but judging from microscope observations, the degradation was close to complete in the trial. It seems the increased slime content, induced by nutrient limitation, greatly increased the biodegradability of the sludge.

This mechanism, leading to low sludge production in the nutrient-limited BAS process, is similar to the microbial mechanism of the so-called low sludge production (LSP) process [12, 13]. In the LSP process, the readily biodegradable organic matter is removed in a first stage designed and operated to favor the growth of free-swimming bacteria. Filter feeding microanimals in the following activated sludge basin then consume the dispersed biomass from this stage. Thus, in both the nutrient-limited BAS process and the LSP process, the low sludge production depends on the biomass formed in a first reactor being consumed by microorganisms in a subsequent activated sludge process. The main difference is in the type of biomass produced in the first stage. The growth of free-swimming bacteria in the first stage of the LSP process requires large amounts of available nutrients. This results in high nutrient consumption and may lead to nutrient discharge problems, as the nutrient content of the dispersed biomass is released as ammonium and phosphate in the activated sludge basin when this biomass is consumed [14]. The slimy sludge produced in the biofilm reactor of the nutrient-limited BAS contains much less nutrients and does consequently not give the same risk of nutrient release and discharge. Another advantage of the BAS system is that the biofilm pretreatment is more compact and more tolerant of disturbances than the pre treatment reactor in the LSP process.

CONCLUSIONS

This study confirms that nutrient-limited biofilm pretreatment of bleached kraft mill effluent (and potentially other types of effluents) before activated sludge treatment can efficiently secure good settling characteristics of the sludge and low sludge production. The pretreatment increases the treatment capacity and decreases operating costs due to decreased sludge handling and lower nutrient requirements.

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INSIGHTS FROM THE AUTHORS

This study is a natural continuation of the work we are doing on optimal design and operation of biological treatment plants for pulp and paper industry effluents.

The nutrient limitation operation is a new concept. All previous work we know about has focused on balancing nutrients or keeping an excess. This research is complementary and has shown previously unknown beneficial effects from operating with nutrients in shortage.

The most difficult aspect of the study was the long response time of biological treatment. We addressed that by very carefully following all trends and running the experiments patiently until the results were stable.

The discovery of the microbial mechanisms behind low sludge production and good sludge separability was a very interesting and surprising finding.

Our next step is to apply the research results in a number of full scale plants.

—Thomas Welander

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