Impact of fine mesh sieve primary treatment on nitrogen removal in moving bed biofilm reactors

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ABSTRACT

The purpose of this project was to investigate the effect of selective particle removal during primary treatment on nitrogen removal in moving bed biofilm reactors (MBBRs). Two small MBBR pilot plants were operated in parallel, where one train treated 2 mm screened municipal wastewater and the other train treated wastewater that had passed through a Salsnes Filter SF1000 rotating belt sieve (RBS) with a 33 µm sieve cloth. The SF1000 was operated without a filter mat on the belt. The tests confirmed that, for the wastewater characteristics at the test plant, Salsnes Filter primary treatment with a 33 µm RBS and no filter mat produced a primary effluent that was close to optimum. Removal of organic matter with the 33 µm sieve had no negative effect on the denitrification process. Nitrification rates improved by 10–15% in the train with 33 µm RBS primary treatment. Mass balance calculations showed that without RBS primary treatment, the oxygen demand in the biological system was 36% higher. Other studies have shown that the sludge produced by RBS primary treatment is beneficial for biogas production and will also significantly improve sludge dewatering of the combined primary and biological sludge.

Key words | biofilms, denitrification, nitrification, particle size separation, primary treatment, rotating belt sieves

INTRODUCTION

Fine mesh rotating belt sieves (RBS) have been very successful for primary treatment of municipal wastewater (Rusten & Ødegaard 2006) and for removal of suspended solids (SS) from industrial wastewater (Nussbaum et al. 2006). However, the market for primary treatment alone is very small and decreasing. To open up a significantly larger market for this technology it is necessary to qualify the fine mesh RBS for use in combination with biological treatment processes that provide secondary and tertiary treatment (Sutton et al. 2008). The problem is that several process consultants and end users believe that fine mesh RBS removes too much organic material and that this is detrimental to the downstream biological process. This may, to a certain degree, be correct for processes with biological phosphorus removal (bio-P) and nitrogen removal by pre-denitrification, because these processes need readily biodegradable organic material. However, large particles are generally slowly biodegradable. The question is how far down in particle size is the optimum particle removal before any negative effects are seen in biological N- and P-removal processes.

Presently the state-of-the-art solution for primary solids separation in wastewater treatment is sedimentation. The performance of the sedimentation process depends on the wastewater composition, the flow rate and the size and design of the sedimentation tanks. Controlling the sedimentation process to exclude a specific particle size from entering the downstream process is impossible. However, this can be done with a fine mesh sieve and a proper control system.

Newcombe et al. (2011) performed a literature review regarding the optimum particle sizes to be removed prior to biological treatment. Since state-of-the-art for primary treatment is settling instead of simple particle size exclusion, no firm conclusions could be drawn. Furthermore, given sufficient time in the biological reactor, particulate organic material will hydrolyze and gradually produce soluble organic material. The optimum particle size cut-off will,
therefore, depend on the type of biological treatment process (activated sludge vs. fixed film), the solids and hydraulic retention times in the biological reactors and the wastewater temperature. However, based on the literature Newcombe et al. (2011) initially expected the optimum particle size cut-off to be in the 15–20 μm range in front of an activated sludge process with biological phosphorus removal and nitrogen removal.

At the University of Stavanger (Stavanger, Norway) a 3-year R&D project was initiated in 2012 to find the optimum particle size cut-off for particle removal in front of biological nitrogen removal processes with pre-denitrification. Removal of too many particles may reduce the carbon-to-nitrogen (C/N) ratio to the point where the nitrogen removal is affected due to reduced denitrification. Not removing enough particles may negatively affect the nitrification process. As a part of this R&D program initial short-term tests were performed using wastewater from two municipal wastewater treatment plants (WWTPs) and both activated sludge and biofilm biomass (Razafimanantsoa et al. 2014a). This was followed by longer term tests (Razafimanantsoa et al. 2014b) with activated sludge sequencing batch reactors (SBRs). For the tested wastewaters the results showed that sieves with 33 μm openings provided the optimum primary treatment when operated without a filter mat on the sieve cloth.

The next step was side-by-side continuous flow testing of the impact of fine mesh sieve primary treatment on nitrogen removal in moving bed biofilm reactors (MBBRs), where one train received screened wastewater and the other train received wastewater that had passed through a 33 μm Salsnes Filter (SF) fine mesh RBS.

**EXPERIMENTAL SET-UP**

The MBBR pilot plants were located at the Nordre Follo WWTP, south of Oslo, Norway. The Nordre Follo WWTP is a large MBBR plant with combined pre- and post-denitrification. Description and performance of this plant can be found in Rusten & Ødegaard (2007).

**Pilot-plant descriptions**

Coarse screened wastewater was pumped from just downstream of the screens at the Nordre Follo WWTP and passed through either a 2 mm screen or a RBS with 33 μm sieve cloth.

The RBS was a standard SF1000 (Salsnes Filter, Namsos, Norway) with a submerged sieve cloth area of 0.25 m². It was operated without a filter mat and this was achieved by running the sieve at a very low wastewater flow (5–6 m³/h) and with a high belt speed (5.0–7.5 cm/s). Fresh batches of wastewater were prepared three times per week and stored at ambient temperature (about 15 °C) in tanks with mechanical mixers to prevent settling of particulate matter. Batches of wastewater were prepared in the afternoon, when the influent wastewater composition to this plant normally is close to the 24 h average composition. For practical reasons it was impossible to collect the 2 mm screened wastewater and the wastewater that had passed through the 33 μm sieve at the exact same time. It was random which batch was collected first and the time lapse between the collection of the two batches was between 19 and 40 minutes.

The small MBBR pilot plants for nitrogen removal were operated in parallel, where one plant (Train A) treated the 2 mm screened wastewater and the other plant (Train B) treated the wastewater that had passed through the 33 μm sieve cloth. A simplified flow chart of one of the trains is shown in Figure 1. Each train had four reactors in series, where reactors 1 and 2 were anoxic, and reactors 3 and 4 were aerobic. Anoxic reactors had mechanical mixers and aerobic reactors had diffusers for aeration at the bottom of the tanks. All reactors had 60% fill (bulk volume of carriers per wet volume of reactor) of the Kaldnes K1 biofilm carriers, resulting in a protected biofilm surface area of 300 m²/m³ of wet reactor volume. The water volume displaced by the biofilm carriers was 10.6%. All anoxic reactors had a wet volume of 4.0 L and aerobic reactors had a wet volume of 6.0 L, resulting in 40% anoxic volume and 60% aerobic volume. Nitrified effluent was recycled from reactor 4 to reactor 1 at approximately twice the influent flow.

**Monitoring, sampling and analyses**

Mixing conditions and water levels in the storage tanks were checked daily. MBBR influent flows and recirculation flows were checked and adjusted daily. Dissolved oxygen (DO), pH and temperature were measured daily in all biological reactors.

Samples of 2 mm screened wastewater, 33 μm sieved wastewater and final effluent from the two MBBR trains were taken four to six times per week. These samples were analyzed for SS, volatile suspended solids (VSS), total chemical oxygen demand (TCOD), filtered chemical...
oxygen demand (FCOD), total nitrogen (TN), total nitrogen on filtered sample (FTN), NH₄-N, NO₂-N, NO₃-N, total phosphorus (TP), total phosphorus on filtered sample (FTP), and PO₄-P. Water samples from every biological reactor were taken twice per week and analyzed for SS, TCOD, FCOD, NH₄-N, NO₂-N, NO₃-N, and PO₄-P. Glass fiber filters (Whatman GF/C) were used for filtration of samples and for measuring SS. SS was analyzed according to Standard Method SM 2540 D and E (APHA 2005). All chemical analyses, on the other hand, were done using Dr Lange test cuvette kits, a thermostat LT200 and a Spectrophotometer DR 2800 (Hach Lange, Düsseldorf, Germany). Biofilm carriers were sampled once every 2 weeks and attached biomass was measured as total solids (TS). The method consisted of collecting 15 biofilm carriers from each reactor, drying them at 105 °C overnight, cooling and measuring the weight of carriers and attached biomass. The carriers were afterwards soaked in full strength domestic sodium hypochlorate solution for 30 minutes, then washed and scrubbed with warm water to remove all traces of biomass. The washed carriers were then dried at 105 °C overnight, cooled, and the weight of the clean carriers was recorded.

Start-up procedure and operating parameters for MBBRs

The biofilm carriers used for the pilot reactors already had a mature biofilm on them, since they were taken from anoxic pre-denitrification and aerobic nitrification reactors, respectively, at the full-scale MBBR plant. This explains the very short start-up period of only 3 weeks.

Operating parameters for the pilot-scale MBBRs are shown in Table 1. During the 11 weeks of testing the average empty bed hydraulic retention time, based on influent flow, was 7.1 h. Recirculation flow was approximately twice the influent flow.

RESULTS AND DISCUSSION

The overall results are shown in Table 2. The 33 μs sieve cloth with no filter mat removed on average 41% of SS, 31% of TCOD, 12% of TN and 14% of TP. The MBBR plants did not have final solids separation stages, so when analyzing overall removal of organic matter and nitrogen, effluent concentrations measured on filtered (GF/C)
It has been shown in a Dutch study (Ruiken et al. 2013) that the majority of the solids removed by fine mesh sieves (350 μm mesh) were paper fibers, and this indicated that the COD of the removed particles may be less biodegradable than the COD of the particles that passed through to the biological reactors. One of the indications of the cellulose nature of the sieve sludge was the absence of proteins, shown by removal of only about 1% nitrogen over the sieves. However, in the present study the fine mesh sieve removed 12% of TN, 31% of total organic N and 58% of particulate organic N. Since the removal of particulate organic N was very close to the removal of SS, there is no evidence that the majority of solids separated by the sieve in the present study were of cellulose nature.

### Sludge production

Sludge productions were calculated with a mass balance approach, first calculating the average daily sludge productions for a given train and then dividing by the average daily flow through that train. Average sludge productions were 199 mg SS/L for Train A (2 mm screen) and 244 mg SS/L (114 mg SS/L primary + 130 mg SS/L biological) for Train B (33 μm sieve). The specific sludge yield for biological sludge was 0.41 g SS/g TCOD removed for both trains. Using the SF fine mesh sieve increased the total sludge production by about 20–25%. However, almost half of the sludge was primary sludge, which can dewater to a high solids concentration and has a significantly higher methane gas potential than biological sludge (Gavala et al. 2003). In a recent survey of 19 municipal treatment plants with Salsnes Filter RBS primary treatment the sludge was dewatered in simple screw presses and with no use of chemicals to an average dry solids (DS) concentration of 27%. The sieved sludge had significantly higher volatile solids (VS) content than primary sludge from conventional clarifiers, with mean values of 92% of DS and 81% of DS, respectively. In addition methane potential testing showed that the sieved sludge also had 20% higher CH₄ production in anaerobic digesters than settled sludge, 345 NmL CH₄/g VS versus 287 NmL CH₄/g VS (Paulsrud et al. 2014).

### Biological treatment

Since the fine mesh RBS removed a higher percentage of the total COD than of the total N, the C/N ratio based on total COD was significantly lower for Train B than for Train A. Influent C/N ratios to Train A (2 mm screen) were 12.4 ± 2.8 g total COD/g total N and 2.9 ± 1.1 g BSCOD/g

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**Table 2** | Overall results for the two pilot-scale MBBR plants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2 mm screen, Train A</th>
<th>33 μm sieve, Train B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Influent (mg/L)</td>
<td>Effluent (mg/L)</td>
</tr>
<tr>
<td>SS</td>
<td>281 ± 96</td>
<td>204 ± 85</td>
</tr>
<tr>
<td>Total COD</td>
<td>521 ± 129</td>
<td>302 ± 106</td>
</tr>
<tr>
<td>Filtered COD</td>
<td>168 ± 53</td>
<td>45 ± 9</td>
</tr>
<tr>
<td>BSCOD</td>
<td>118 ± 45</td>
<td>–</td>
</tr>
<tr>
<td>Total N</td>
<td>44.0 ± 11.9</td>
<td>23.2 ± 5.2</td>
</tr>
<tr>
<td>Filtered TN</td>
<td>33.6 ± 9.9</td>
<td>15.1 ± 6.3</td>
</tr>
<tr>
<td>Total organic N</td>
<td>11.5 ± 4.1</td>
<td>14.0 ± 5.1</td>
</tr>
<tr>
<td>Filtered organic N</td>
<td>1.8 ± 1.8</td>
<td>2.4 ± 1.7</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>31.7 ± 10.7</td>
<td>1.3 ± 2.3</td>
</tr>
<tr>
<td>NO₂-N</td>
<td>0.03 ± 0.02</td>
<td>0.21 ± 0.19</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>0.41 ± 0.2</td>
<td>10.9 ± 4.2</td>
</tr>
<tr>
<td>Total P</td>
<td>4.1 ± 1.4</td>
<td>3.3 ± 1.5</td>
</tr>
<tr>
<td>Filtered TP</td>
<td>1.7 ± 0.6</td>
<td>1.1 ± 0.6</td>
</tr>
</tbody>
</table>

*Shows averages and standard deviations.*

Samples were used. Based on this, average removal for total COD was 91% for both Train A and Train B. Average removal of total N was 68% for Train A (2 mm screen) and 66% for Train B (33 μm sieve). Average removal of total P was 70% for both trains. P was removed both as particulate P and as P assimilated in to the produced biomass. These results would be valid for plants with ‘perfect’ separation processes, for example use of microfiltration membranes. A previous pilot test at the Nordre Follo WWTP, with MBBRs and a shallow settling tank, resulted in average values of 7 mg/L SS and 5 mg/L particulate COD in the settled effluent (Rusten et al. 1995a). Assuming settling tanks with similar performance were used in the current test, the removal efficiencies for total N and total COD would decrease with less than 1% for both trains.

Biodegradable soluble COD (BSCOD) and organic N values in Table 2 were not measured directly, but were calculated from measured FCOD and measured N values, respectively. BSCOD is based on the measured FCOD in the influent or in a given reactor, minus the measured FCOD in the effluent from a fully nitrifying reactor (Rusten et al.995a). Since reactors A4 and B4 had full nitrification, the influent BSCOD on any given day was calculated as the influent FCOD to the train minus the effluent FCOD from that train on that day.
total N. Influent C/N ratios for Train B (33 μs sieve) were 9.5 ± 2.1 g total COD/g total N and 2.8 ± 0.9 g BSCOD/g total N. After the 33 μs sieve the total C/N-ratio was close to what was considered the optimum for achieving good conditions for both nitrification and denitrification, based on previous activated sludge SBR tests (Razafimanantsoa et al. 2014b).

**Nitrification**

Ammonium loads, nitrification rates, DO concentrations and ammonium concentrations in the aerobic reactors are summarized in Table 3. All loads and rates were temperature compensated to 20 °C using a temperature coefficient for nitrification of θ = 1.09 (Rusten et al. 1995b). Reaction rates in reactor 4 were limited by low ammonium concentrations most of the time. In reactor 3 the reaction rates were sometimes limited by the DO concentration and sometimes by the NH₄-N concentration. Train B had slightly lower DO concentrations in reactor 3 than Train A. Nevertheless, nitrification rates in Train B were 10–15% higher than in Train A.

Ammonium loads and nitrification rates for individual reactors on individual days are shown in Figure 2, temperature compensated to 20 °C, and all these data points were included in the calculations in Table 3. Nitrification in MBBRs have previously been shown to be significantly impacted by variations in COD load as well as SS concentrations (Rusten et al. 1995b, 2000). Thus, the scatter in Figure 2 is typical for the first aerobic reactor in a train of MBBRs. In the first aerobic reactor there may be highly variable loads of organic matter and SS from day to day, and since nitrification in this first aerobic reactor tends to be unstable the variations have a large impact on the nitrification rates. As expected, the scatter is larger in A3 than in B3, since Train A received significantly more TCOD and SS than Train B. Most data points with fairly low nitrification rates at high NH₄-N loads are from reactors 3 or 4 in Train A. This shows the advantage on nitrification achieved in the present study by using Salsnes Filter fine mesh RBS to remove larger particles, and the organic matter associated with these particles, prior to biological treatment.

**Denitrification**

In order to compare the denitrification rates in the two trains NO₂⁻-N and DO have been converted to equivalent amounts of NO₃⁻-N (NO₃⁻-Nₑq), since both NO₂⁻-N and DO consume carbon source and require removal by the microorganisms in the biofilm. 1 mg NO₂⁻-N is equivalent to 0.6 mg NO₃⁻-N, and 1 mg O₂ is equivalent to 0.35 mg NO₃⁻-N. Concentrations, NO₃⁻-Nₑq loads and denitrification rates are summarized in Table 4. Denitrification rates on individual days are shown in Figure 3, and all these data points were included in the calculations in Table 4. All loads and rates were temperature compensated to 20 °C using a temperature coefficient for denitrification of θ = 1.07 (Rusten et al. 1997).

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**Table 3 | Nitrification in reactors 3 and 4 of the two MBBRs**

<table>
<thead>
<tr>
<th>Reactor and parameter</th>
<th>2 mm screen, Train A</th>
<th>33 μs sieve, Train B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg. ± Std.</td>
<td>Median</td>
</tr>
<tr>
<td>Reactor 3:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonium load, g NH₄-N/m²-d</td>
<td>1.18 ± 0.45</td>
<td>1.14</td>
</tr>
<tr>
<td>Removal rate, g NH₄-N/m²-d</td>
<td>0.87 ± 0.25</td>
<td>0.85</td>
</tr>
<tr>
<td>Reactor DO, mg/L</td>
<td>6.95 ± 1.09</td>
<td>6.94</td>
</tr>
<tr>
<td>Reactor NH₄-N, mg/L</td>
<td>2.48 ± 2.64</td>
<td>1.02</td>
</tr>
<tr>
<td>Reactor 4:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonium load, g NH₄-N/m²-d</td>
<td>0.31 ± 0.36</td>
<td>0.14</td>
</tr>
<tr>
<td>Removal rate, g NH₄-N/m²-d</td>
<td>0.22 ± 0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>Reactor DO, mg/L</td>
<td>5.94 ± 1.54</td>
<td>5.75</td>
</tr>
<tr>
<td>Reactor NH₄-N, mg/L</td>
<td>0.77 ± 1.29</td>
<td>0.17</td>
</tr>
</tbody>
</table>

All loads and rates are temperature compensated to 20 °C.
The scatter in the data in Figure 3 is as expected for denitrifying MBBRs that receive wastewater with highly variable influent BSCOD concentrations, since pre-denitrification rates in MBBRs have been found to be almost linearly dependent on the BSCOD concentration in the influent to the reactor (Rusten et al. 2000). Influent concentrations to the first pre-denitrification reactor ranged from 15 to 83 mg BSCOD/L for Train A and 13 to 60 mg BSCOD/L for Train B.

On average Train A (2 mm screen) had about 5% higher denitrification rate in reactor 1 than Train B (33 μs sieve). DO in anoxic reactors inhibits the denitrification process and higher DO in reactor 1 in Train B than in Train A (see Table 1), plus the slightly higher influent BSCOD concentrations for Train A, are the most likely reasons for the slightly higher denitrification rate in Train A. We would expect the influent BSCOD concentration to be fairly similar for the two trains, and the slightly higher concentration in Train A is probably due to some hydrolyses of the particulate COD during the storage of batches of influent wastewater. Looking at the overall denitrification over reactors 1 + 2, the average denitrification rate was about 3% higher in Train B than in Train A. This shows that removal of organic matter by the 33 μs Salsnes Filter RBS did not have any negative impact on the denitrification process in the present study.

Looking at the NO3-Neq concentrations from reactor 2 and in the final effluent, they were slightly higher in Train B than in Train A, even though both trains had almost identical denitrification rates. The main reason for this was that the DO in reactor 4 was significantly higher than necessary in Train B (see Table 1), where the nitrification process was ammonium limited, and due to recycling this increased the NO3-Neq load on the anoxic reactors. Train A had 2% higher removal of total N than Train B. However, in a
full-scale plant with good DO control the NO₃-N eq in Train B could easily be reduced by more than 1 mg NO₃-N eq/L, by reducing the DO concentration in reactor B4 without affecting the nitrification rate. This would decrease the average effluent concentration of filtered TN to the same value as in Train A, and the two trains would have the same total N removal efficiency.

Biomass and oxygen balance

Table 5 shows the average amount of biomass in each reactor. The average amount of biomass on the biofilm carriers varied from a low of 12 g TS/m² biofilm surface area for reactor 4 in Train B (33 μs sieve), to a high of 23 g TS/m² for reactor 2 in Train A (2 mm screen).

Solids retention time (SRT), or sludge age, is a parameter that is widely used for activated sludge systems, but not for biofilm processes. In biofilm systems different parts of the biofilm will have a different age. However, for MBBRs the average sludge age, based on the daily biomass production and the total amount of biomass attached on the biofilm carriers, has been a useful parameter for calculating oxygen demand using the equations in the German design guidelines (ATV 2000). For the entire test period the average values for total SRT were 8.0 days for train A (2 mm screen) and 10.5 days for train B (33 μs sieve). Aerobic SRTs were about 4.0 days and 5.3 days for train A and train B, respectively.

Using the standard ratio in the German design guidelines of COD/BOD₅ = 2.0, the specific oxygen demand for removal of organic matter was calculated as 0.56 g O₂/g COD for train A (8.0 d SRT) and 0.59 g O₂/g COD for train B (10.5 d SRT), both at the actual temperature of 19 °C. The oxygen demand for nitrification were calculated using the standard value of 4.3 g O₂/g N nitrified, and the oxygen credits for denitrification were calculated, using the standard value of 2.9 g O₂/g NO₃-N eq removed. Altogether, the total oxygen demand for the pilot plants were 22.9 g O₂/d for train A and 16.9 g O₂/d for train B. This means that without the Salsnes Filter 33 μs RBS, the oxygen demand in the biological stage was 36% higher.

CONCLUSIONS

Pilot-plant MBBR tests for nitrogen removal confirmed that, for the wastewater characteristics at the test plant, Salsnes Filter primary treatment with a 33 μs rotating belt sieve and no filter mat produced a primary effluent that was close to optimum. The rotating belt sieve removed on average 41% of SS, 31% of TCOD, 12% of TN and 14% of TP.

Removal of organic matter with the 33 μs sieve had no negative effect on the denitrification process. Nitrification rates improved by 10–15% in the train with 33 μs rotating belt sieve primary treatment. Mass balance calculations showed that without rotating belt sieve primary treatment, the oxygen demand in the biological system was 36% higher.

The sludge produced by rotating belt sieve primary treatment is beneficial for biogas production (Paulsrud et al. 2014) and will also significantly improve sludge dewatering of the combined primary and biological sludge.

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