Fermentation and disintegration of sludge to promote biological nutrient removal


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Abstract: Primary sludge collected from 5 different full-scale sewage treatment works in the UK were fermented in 5 L vessels mechanically stirred at 20°C for 4 days. During the fermentation process the VFAs content increased by up to 8.8 g/L (initial concentration of 3.5 g/L). Acetic acid and propionic acid were the main products formed and the production of VFAs was linked with the suspended solids and volatile solids content of the primary sludge. In comparison, surplus activated sludge (SAS), obtained from a 1 m³ pilot scale BNR process was mechanical disintegrated using a deflaker. The mechanical disintegration of the SAS increased the VFAs from 19 to 530 m/L and the soluble COD from 159 to 500 mg/L. The products of the fermentation process and SAS disintegration were used in laboratory tests to predict the biological phosphorus and nitrogen removal during BNR. Acetate, which is a chemical carbon source frequently used to enhance BNR was also used. The carbon source obtained from fermentation and disintegration treatments were capable of enhancing P release and denitrification up to 0.144 mg P/L-min and 0.04 mg NO₃/g VSS-min, respectively, in comparison to acetate (0.077 mg P/L-min and 0.023 mg NO₃/g VSS-min). The results demonstrate that hydrolysed or disintegrated primary or secondary sludges enhanced P release and denitrification at a higher rate than chemical carbon sources such as acetate.

Keywords: deflaker; denitrification; phosphorus release; primary sludge; surplus activated sludge; volatile fatty acids

INTRODUCTION

Removal of nitrogen and phosphorus from wastewater effluents is important to ensure environmental protection of surface waters. High concentrations of nutrients in rivers have been pointed out to be responsible for eutrophication, oxygen depletion in the river waters and to stimulate algae growth (Mulkerrins et al. 2003). Biological nutrient removal (BNR) has been proposed as an efficient process to remove nutrients from wastewater. However for the microorganisms to be able uptake phosphorus (P) and nitrogen (N) during the BNR process the wastewater must have a sufficient carbon concentration (Abu-ghararah and Randal, 1991). To remove 1 mg of phosphorus, 6-10 mg of VFAs or 20 mg COD equivalent of acetic acid are required (Abu-ghararah and Randal, 1991). Hence the addition of chemicals such as ethanol, methanol or acetate to enhance the BNR process is sometimes necessary but the costs associated are significant and the need to have chemical storage facilities on site decreases its attractiveness. VFAs are the most suitable carbon source for BNR resulting in high rates of P and N removal. The release and production of VFAs can be promoted by destroying the sewage sludge or by fermentation and this way sludges are re-used decreasing the overall sludge production in a treatment works and the BNR efficiency is assured. Sludge disintegration has been demonstrated to be able to increase the SCOD and VFA content by disrupting cells using pressure (Muller 2000). However, there is little information about the application of the disintegrated sludge to BNR in order to improve P and N removal (Kamps et al. 2007). Fermentation of primary sludge is an easy process to operate and it produces volatile fatty acids (VFAs) (Hatziconstantinou, 1996; Hatziconstantinou, 2003; Urbain et al. 2001; Bixio et al. 2001). The sludge retention time in the fermenter is a critical point to achieve high VFAs production. Appropriate retention time must be provided in order to obtain good levels of hydrolysis and acidogenesis without methane gas formation. Hence sludge retention times must be lower than 6 to 10 days at temperatures of 20°C to 10°C, respectively (Grady et al. 1999).
The aim of this study was to examine the ability of different types of primary sludge obtained from full-scale sewage treatment works to ferment and produce VFAs and relate the characteristics of primary sludge to the soluble carbon production. This is an important result that can allow some degree of prediction regarding VFAs production using a particular type of primary sludge. A mechanical process widely used in the pulp and paper industry was also used to promote the release of VFAs from SAS. A comparison of BNR efficiency when using internal and external carbon source was performed.

MATERIALS AND METHODS

Fermentation of primary sludge

Five different full-scale sewage treatment at works at Yorkshire, UK with population equivalents of 499065, 386123, 373985, 373985, 573394 and 18914 for Sites 1, 2, 3, 4 and 5, respectively, were sampled for primary sludge. Four and half litres of primary sludge were fermented in 5L vessels (quickfit flask 100 mm flange bore, height 290 mm QRE-130-B, Fisher, UK) for 4 four days at room temperature (20-23°C). The sludge was mechanically mixed at a constant speed of 0.7 \( \cdot \) g by overhead motor stirrers (Heidolph RZR 2020 and 2102, Schwabach, Germany). Anaerobic conditions were assured by keeping the fermentation vessels sealed. Every 12h, 60 mL of sludge were sampled for VFAs analyses and every 24h for total suspended solids (TSS), volatile suspended solids (VSS), soluble chemical oxygen demand (SCOD), pH, ammonia (NH\(_4^+\)) and soluble P analyses. All fermentations were performed in duplicate. At the end of the 4 days, the fermentation product obtained from the sludge collected at Site 1 was centrifuged for 20 min at 8804 \( \cdot \) g (Hettich Zentrifugen, Tuttlingen, Germany) and the supernatant stored frozen at -20°C for further tests.

Mechanical disintegration of surplus activated sludge

Five litres of thickened surplus activated sludge (SAS) collected from a 1 m\(^3\) BNR pilot-plant was mechanically disintegrated using a 10" Pilao DTD Spider Deflaker with a 30 kW motor fitted with 230 mm discs with 3 active cell layers according to Kampas et al. (2007). The disintegration process was conducted as a batch. A portion of the disintegrated sludge was centrifuged for 20 minutes at 8804 \( \cdot \) g (Hettich Zentrifugen, Tuttlingen, Germany). The centrifugation supernatant and disintegrated sludge were used fresh for further tests.

BNR tests

Phosphorus release and denitrification testes were conducted in 2.5 L plexi-glass vessels at 25°C. A mixture of 1 L wastewater and 1 L returned activated sludge (RAS), collected from a full-scale BNR plant in Derbyshire, UK was placed in each on the 5 vessels used for BNR tests. Nitrogen was continuously supplied to the headspace of the vessels to ensure anaerobic conditions. The vessels were mixed with magnetic stirrers at 20.2 \( \cdot \) g and the pH and dissolved oxygen (DO) continuously monitor. Vessel 1 was used a control and no addition of extra carbon source was performed, vessel 2 was spiked with a solution of 10 mg/L of acetate and vessels 3, 4 and 5 were spiked with liquor obtained from the fermentation of the primary sludge, deflaker sludge and supernatant of sludge deflaker, respectively. The amount of carbon added to each vessel was matched in terms of COD (50 mg/L) and VFAs (3.5 mg/L) contents (Table 1). For the denitrification tests, 20 mg KNO\(_3\)/L was added to each vessel at the beginning of the experiment. The tests were performed for 2 and 20h for the phosphorus release and denitrification tests, respectively. Samples of 60 mL were taken every 30 min for the first 2 hours. For the denitrification test a last sample was taken after 20 hours. The samples were filtered through a syringe filter of 0.45 \( \mu \)m, stored at 4°C before VSS, COD, soluble P and nitrate (NO\(_3^-\)) analyses were performed. P and N rates were calculated after 120 and 90 min, respectively.
Analytical methods

The samples were centrifuged at 8804 g for 20 min (Hettich Zentrifugen, Tuttingen, Germany) and the supernatant filtered through a 0.45 μm (glass-fiber filter paper) prior to analyses. Chemical organic demand, NO₃-, NH₄⁺, soluble P were determined using Merck Spectroquant cell test (Darmstadt, Denmark) according to the manufacturer instructions. Solids determination, TSS and VSS, was performed according to the Standard Methods (1998). All the analyses were performed in duplicate.

For VFAs determination, 9 ml of the filtrate was placed in 10 ml plastic tubes and acidified with 10 l of sulfuric acid 98% and frozen until HPLC analyses performed according to the method described by Bjornsson et al. (2000). An external standard was used to quantify the VFAs concentration: acetic acid, propionic acid, butyric acid and valeric acid.

RESULTS AND DISCUSSION

Primary sludge fermentation

Fermentation of primary sludge is a valuable process to produce soluble organics from sewage sludge in anaerobic conditions (Urbain et al. 2001; Bixio et al. 2001). Initial concentrations of SCOD in the primary sludge varied from 2.3 g/L (Site 3) to 5.6 g/L for Site 1 and were increased by an average of 2.2 fold after the 4 days of fermentation (Table 2).

The fermentation process occurs in two main steps: hydrolysis and acidogenesis. During hydrolysis the long chain molecules are broken down into smaller dissolved molecules by extracellular enzymes that are then converted to VFAs during the acidogenesis step (Moser-Engeler et al. 1998). Solubilisation of COD is thought to be mainly due to the production of VFAs, with more than 85% of the SCOD generated being associated with VFAs (Moser-Engeler et al. 1998). A correlation between VFAs production and SCOD was found, demonstrating that the increase in SCOD was linearly related with the VFAs production (Figure 1). The initial VFAs concentration in the 5 studied sites varied from 2.2 to 3.5 g/L for the sludge collected at Site 5 and Site 1, respectively, to reach values between 4.6 and 8.8 g/L for Sites 3 and Site 5, respectively, after the four days of fermentation (Table 2).

Biological nutrient removal efficiency is highly dependant on the amount and quality of internal carbon source present. Type of VFA added to the process has been demonstrated to influence the BNR performance (Abu-ghararah and Randal, 1991). According to the results obtained for VFAs production, after the 4 days of fermentation mainly acetic acid (average percentage of 40.6%) and propionic acid (average percentage of 36.7%) were produced. These results were in the range of the percentage found by Wentzel et al. (1988) with 43% for acetic acid and 41% for propionic acid produced after fermentation of primary sludge at 20°C. VFAs production was observed to mainly occur between the beginning of the tests and 40h (production rates between 0.118 g VFA/h (Site 1) to 0.188 g VFA/h (Site 5)). Hence the most important degradation process was the rapid use of readily available substrates to produce VFAs. Between 46 h and 80h, fermentation degradation processes occurred at a lower rate and the VFAs formation rates decreased to values between 0.03 g VFA/h (Site 1) and 0.09 g VFA/h (Site 2).
Figure 1 Correlation between SCOD and VFAs content in COD equivalent (VFAs-COD, calculated according to Lie et al. (1997) that reported COD equivalent constants of 1.066 for acetic acid, 1.512 for propionic acid, 1.816 for butyric acid, and 2.036 for valeric acid), for Site 1 ( ), Site 2 ( ), Site 3 ( ), Site 4 ( ) and Site 5 +. The correlation coefficients (R2) for the curves varied between 0.87 for Site 5 and 0.96 for Site 2.

Primary sludge composition in TSS and VSS were important parameters that influenced the production of VFAs as a correlation was found between TSS, VSS and VFAs production (Figure 2). In order to predict VFAs production, sufficient TSS and VSS must be present (Banister and Pretorius, 1998) with high solids content promoting higher VFAs production (Zeng et al. 2006). The primary sludge collected at Sites 1 and 5 contained high VSS and TSS contents in comparison with the other sites and those were also observed to have the highest VFAs production (Table 1).

Surplus activated sludge disintegration
The mechanical disintegration of SAS by the deflaker was evaluated in terms of soluble carbon and nutrient release. Surplus activated sludge is mainly constituted by flocs of biomass that developed during activated sludge process. The mechanical disintegration of the sludge using the deflaker was demonstrated to destroy the porous flocs and microflocs releasing the organic matter that links particles together but no definitive conclusions were withdraw regarding the capacity of the deflaker to perform cell lyses (Kampas et al. 2007). The VFAs and SCOD content of the SAS sludge increased after mechanical disruption from 19 mg VFA/L and 340 mg SCOD/L to 530 mg VFA/L and 6180 mg SCOD/L, respectively (Table 3).

Table 3 Effect of sludge mechanical disintegration on SAS in regard to SCOD, VFAs, P and NH₄⁺ release (adapted from Kampas et al. 2007).

<table>
<thead>
<tr>
<th>Raw sludge</th>
<th>SCOD (mg/L)</th>
<th>VFAs (mg/L)</th>
<th>Soluble P (mg/L)</th>
<th>NH₄⁺ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>110-340</td>
<td>0-19</td>
<td>107-159</td>
<td>8-10</td>
</tr>
<tr>
<td>Deflaked sludge</td>
<td>1200-6180</td>
<td>110-530</td>
<td>420-500</td>
<td>50-60</td>
</tr>
</tbody>
</table>

NH₄ and P release during primary sludge fermentation and SAS disintegration
During fermentation and mechanical disintegration of sludge both P and N were released from the organic matter and solubilised. This re-solubilisation of nutrients into the wastewater is seen as major drawback of using sewage sludge for BNR enhancement. During fermentation of the primary sludge ammonia is released from the degradation of proteins and phosphorus is released from the hydrolysis of intracellular polyphosphate (Gerardi, 2003). The N and P concentrations were observed to increase during the fermentation period and due to the action of the deflaker (Table 2 and 3). During the fermentation of primary sludge, a strong correlation was observed between the increase in acetic acid and ammonia release (correlation factors R² of 0.74, 0.95, 0.96, 0.84 and 0.73 for Site 1, 2, 3, 4 and 5, respectively). The initial concentrations of soluble P in the primary sludge were comprised between 3.45 mg P/L (Site 2) and 50.3 mg P/L (Site 1). Concentration of acetic acid
produced in COD equivalent was also clearly correlated with phosphorus release for each site (correlation factors from 0.88 to 0.94 were calculated) demonstrating a strong link between the two parameters.

The disintegration of SAS was observed to enhance P and N release with an increase from 159 mg P/L and 10 mg NH\textsubscript{4}\textsuperscript{+}/L to 500 mg P/L and 60 mg NH\textsubscript{4}\textsuperscript{+}/L, respectively, i.e., 3.5 (P) and 6 (N) fold higher (Table 3). On average, the P and NH\textsubscript{4}\textsuperscript{+} release from the fermentation of primary sludge was only 2.1 and 4 fold higher than the initial concentration. Hence, sludge disintegration was demonstrated to promote higher nutrient release than sludge fermentation.

**BNR tests**

Predictive test can be used to estimate the BNR performance using specific carbon source. These tests are based on the P release after a specific period of time and the denitrification rates, giving an indication of P and N removal, respectively. Two tests were conducted in order to match the carbon addition in VFAs concentration and SCOD. The main goal of performing the two tests was to observe the influence of SCOD other than VFAs in the BNR tests. The phosphate uptake during the aerobic phase is higher than the phosphate release during the anaerobic stage; hence the more phosphate released, the greater the phosphorus uptake that could be expected under aerobic conditions. When the carbon addition was first matched in terms of VFAs the highest P release rates were obtained for deflaked supernatant and deflaked sludge with values of 0.098 and 0.097 mg P/L-min, respectively. The fermentation product was not as effective to enhance P release and the rate measured was 0.043 mg P/L-min. For acetate the P release rate was the lowest observed 0.025 mg P/L-min (Figure 3). Similar results were obtained in the denitrification tests with the highest denitrification rates being measured for the deflaker sludge and supernatant 0.039 and 0.036 mg NO\textsubscript{3}/g VSS-min, respectively, closely followed for the fermentation product 0.031 mg NO\textsubscript{3}/g VSS-min and for acetate the N release rate was as low as 0.010 mg NO\textsubscript{3}/g VSS-min (Figure 3).

When addition of carbon was matched in terms of SCOD the highest phosphorus release rate was obtained for deflaked sludge (0.114 mg P/L-min). The second and third highest rates were measured for the fermentation product (0.099 mg P/L-min) and deflaker supernatant (0.078 mg P/L-min). The lowest P release rate was observed in the acetate vessel (0.077 mg P/L-min) (Figure 3). In the denitrification tests very similar rates were measured for the deflaked sludge, the correspondent supernatant and product of fermentation (0.038, 0.040 and 0.039 mg NO\textsubscript{3}/g VSS-min, respectively) and for acetate was 0.023 mg NO\textsubscript{3}/g VSS-min. The denitrification rates obtained are the same range of those found by Delgenes et al (1998) 0.03 mg NO\textsubscript{3}/g VSS-min when using anaerobic digestion coupled with sequencing batch reactor.

![Figure 3. BNR test regarding phosphorus release rate (A) and denitrification rate (B) when the carbon addition was matched in terms of VFAs (white bars) and COD (black bars) in the vessel 1: control, 2: acetate, 3: product of fermentation from Site 1, 4: deflaked sludge and 5: deflaked sludge supernatant.](image-url)
From the results presented, it is clear that the deflaked products and the fermentation products were able to induce higher P releases and denitrification rates than just acetate. Hence, disintegration products and fermentation product contained other substrates than acetate that additionally enhanced P release and denitrification. According to Moser-Engeler et al. (1998) 85% of the soluble COD generated during sludge fermentation is associated with the VFAs. The percentage found for this study was VFAs-COD content 82 to 86% of the SCOD. Hence when matching the carbon addition in SCOD content other soluble substrates beside VFAs were added to the BNR tests. Consequently, the P release rates and denitrification rates were observed to be in average 1.3 and 1.1 fold higher when the carbon was matched in SCOD. Furthermore, deflaked sludge and deflaked supernatant displayed higher P release and denitrification rates than the fermentation product. The cause for this occurrence was not completely understood but it was suspected that the freezing and thawing of the fermentation product prior to the BNR tests could have promoted the degradation of VFAs and SCOD particles and decreased the efficiency of this substrate. On the other hand, larger volumes of deflaked products were used for the BNR tests compared with the fermentation product. Bearing in mind that P and N release were observed during sludge disintegration and fermentation, it is important to keep the volumes of the added extra carbon sources to a minimum. An estimation of the increase of soluble P and NH₄⁺ to the BNR process was calculated assuming that the products of fermentation and disintegration were added at the same volume ratio as in the BNR test in regard to COD match (Table 4). The concentration of P in the BNR process increased by 3.28 mg/L, when using deflaked products as carbon source. This was regarded as substantial and for this reason the use of the fermentation products for the BNR process was recommended.

CONCLUSION

Both fermentation of primary sludge and SAS disintegration with a deflaker were capable of increasing the VFAs and SCOD of the respective sludges. Overall the fermentation of primary sludge produced a 2.2 fold increase in VFAs. The VFAs were shown to be a suitable carbon source for BNR processes and did not cause any detrimental effects i.e. did not significantly increase the contents of P and N in the BNR mixed liquors. P release and denitrification were better using a mixture of VFAs than acetate only.

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REFERENCES


