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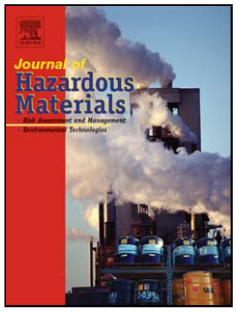

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Comparison between disintegrated and fermented sewage sludge for production of a carbon source suitable for biological nutrient removal

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Abstract

There is a need to investigate processes that enable sludge re-use whilst enhancing sewage treatment efficiency. Mechanically disintegrated thickened surplus activated sludge (SAS) and fermented primary sludge were compared for their capacity to produce a carbon source suitable for BNR by completing nutrient removal predictive tests. Mechanically disintegration of SAS using a deflaker enhanced volatile fatty acids (VFAs) content from 92 to 374 mg l^{-1} (4.1 fold increase). In comparison, primary sludge fermentation increased the VFAs content from 3.5 g l^{-1} to a final concentration of 8.7 g l^{-1} (2.5 fold increase). The carbon source obtained from disintegration and fermentation treatments improved phosphate (PO_4-P) release and denitrification by up to 0.04 mg NO_3-N g^{-1} VSS min^{-1} and 0.031 mg PO_4-P g^{-1} VSS min^{-1}, respectively, in comparison to acetate (0.023 mg NO_3-N g^{-1} VSS $min^{-1}$and 0.010 mg PO_4-P g^{-1} VSS min^{-1}). Overall, both types of sludge were suitable for BNR but disintegrated SAS displayed lower carbon to nutrient ratios of 8 for SCOD:PO_4-P and 9 for SCOD:NO_3-N. On the other hand, SAS increased the concentration of PO_4-

P in the settled sewage by a further 0.97 g PO_4-P kg^{-1} SCOD indicating its potential negative impact towards nutrient recycling in the BNR process.

Keywords: denitrification; mechanical disintegration; phosphorus release; primary sludge; surplus activated sludge

1. Introduction

Removal of phosphorus (P) and nitrogen (N) from wastewater effluents is important to ensure environmental protection of surface waters. High concentrations of nutrients in rivers have been related to eutrophication [1]. Biological nutrient removal (BNR) processes are widely used to remove nutrients from wastewater, however for the phosphate accumulating organisms (PAO) and heterotrophic denitrifiers to be able uptake P and reduce nitrate (NO^-_3) respectively, the wastewater must have sufficient carbon to favour their metabolism [2]. It has been reported that 6-10 mg of volatile fatty acids (VFAs) or 20 mg chemical oxygen demand (COD) as acetic acid are required to remove 1 mg of phosphorus [2] and that 3-4 mg COD as acetic acid per 1 mg of total nitrogen are required for denitrification [3]. More recently, a study in a sequencing batch biofilm reactor demonstrated that 7 mg l^{-1} of acetate are required to remove 1 mg P l^{-1} [4]. To achieve the essential carbon to nutrient ratio, the wastewater can be supplemented with an industrial effluent rich in soluble carbon or chemicals such as ethanol, methanol or acetate to the wastewater. However, the dependence of BNR over the existence of local industries or the costs associated with transport and chemical storage facilities can be significant, decreasing the attractiveness of these external carbon sources. Alternatively, a carbon source rich in VFAs, which are the most suitable carbon source for BNR [5], can be produced at the sewage treatment works (STWs) by disintegration or fermentation of sewage sludge. This approach can stimulate sludge re-use as an alternative to anaerobic digestion and potentially improve BNR efficiency [6].

Nevertheless, the question remains as to what sludge source to use and the appropriate mechanism to apply for VFAs production. Fermentation of primary sludge can promote VFAs production [7, 8] and this method is currently used in countries such as South Africa and the USA for internal carbon source production for BNR [9]. The sludge retention time in the fermenter is critical to achieve high VFAs production in order to enhance hydrolysis and acidogenesis without methane gas formation. Hence, the sludge retention time must be lower than 6 to 10 days depending on the temperature 20°C to 10°C, respectively [10, 11]. Fermentation of secondary sludge has been described to be complex due to the composition of the sludge, mainly microbial cells and flocs, which are difficult to breakdown under anaerobic conditions [12-14]. Furthermore, VFAs-COD equivalent production from SAS fermentation has been reported to be low with 21 mg g^{-1} volatile suspended solids (VSS) compared with primary sludge fermentation 226 mg g^{-1} VSS [15]. Alternatively the production of an internal carbon source from secondary sludge can be achieved through mechanical disintegration. This has been demonstrated to increase the soluble chemical oxygen demand (SCOD) and VFAs content by disrupting microbial flocs and cells using pressure and friction forces [16, 17]. However, there is little information about the application of the disintegrated sludge to BNR in order to improve P and N removal [18] and how it compares with primary sludge fermentation.

The aim of this study was to compare fermented primary sludge and disintegrated SAS, both centrifuged supernatant and disintegrated sludge, for producing a carbon source suitable for BNR. The two methods were compared in terms of VFAs production rate, type of VFAs released and SCOD release rates. Furthermore, the nutrient removal potential of the internal carbon sources was determined by completing nutrient removal predictive tests and comparing removal rates with acetate – an external carbon source. The implications of each of the technologies to the overall treatment process were also assessed in relation to the possible internal recycling of nutrients within the STW.

2. Materials and methods

2.1 Mechanical disintegration of surplus activated sludge

Five litres of thickened surplus activated sludge (SAS) was collected from a 1 m^3 BNR pilot-plant and 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. [16]. The disintegration process was conducted as a batch. A portion of the disintegrated sludge was centrifuged for 20 min at 8804×*g* (Hettich Zentrifugen, Tuttlingen, Germany). The centrifuged supernatant and disintegrated sludge were used within hours after disintegration for nutrient removal predictive tests and analysed for VFAs, SCOD, nitrate (NO_3-N), ammonium (NH_4^+) and PO_4-P contents.

2.2 Fermentation of primary sludge

Primary sludge was collected from five full-scale STWs (Yorkshire, UK) with population equivalents (PE) of 499,065, 386,123, 373985, 373,985, 573,394 and 18,914 for Sites 1, 2, 3, 4 and 5, respectively. Four and half litres of primary sludge were fermented in 5 l vessels (quickfit flask 100 mm flange bore, height 290 mm QRE-130-B, Fisher, UK) for 4 days at room temperature (20-23°C). The sludge was mechanically mixed at a constant speed of 0.7×*g* by overhead motor stirrers (Heidolph RZR 2020 and 2102, Schwabach, Germany) with anaerobic conditions promoted by sealing the fermentation vessels. Every 12h, 60 ml of sludge was sampled for VFAs analyses and every 24h for total suspended solids (TSS), SCOD, pH, NH_4^+ and PO_4-P analyses. All fermentations were completed in duplicate. At the end of 80h, the fermentation product obtained from the sludge collected at Site 1 was centrifuged for 20 min at 8804×*g* (Hettich Zentrifugen, Tuttlingen, Germany) and the supernatant stored frozen at -20°C for nutrient removal predictive tests. This fermentation product was selected because it displayed high VFAs production from an initial concentration 2.2 g l^{-1} to a final 6.3 g l^{-1} (2.8 fold increase) and presented typical VFAs contents of fermented primary sludge with 44% acetic acid and 35% propionic acid [19].

2.3 Nutrient removal predictive tests

Phosphorus release and denitrification testes were conducted in 2.5 l plexi-glass vessels at 25°C according to method described by Kampas et al. [20]. 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 of the five vessels used for the nutrient removal predictive tests. Nitrogen gas was continuously supplied to the headspace of the vessels to ensure anaerobic conditions. The vessels were mixed with magnetic stirrers at 20.2×*g* and the pH and dissolved oxygen continuously monitored with stable values at 7.2-7.5 and < 0.15 mg l^{-1}, respectively. Vessel 1 was used as a control without a carbon source addition, vessel 2 was spiked with a solution of sodium acetate and vessels 3, 4 and 5 were spiked with liquor obtained from the fermented primary sludge, mechanically disintegrated SAS and supernatant from the SAS disintegration, respectively. This experimental configuration was used for a total of 4 different tests for phosphorus release and denitrification when the amount of carbon added to each vessel was matched in SCOD (50 mg l^{-1}) and total VFAs (3.5 mg l^{-1}) contents (Table 1).

For the denitrification tests, 20 mg KNO_3 l^{-1} was added to each vessel at the beginning of the experiment to ensure sufficient nitrate in the wastewater. The tests were completed for 2 and 20h for the phosphorus release and denitrification tests, respectively. Samples of 60 ml were taken every 0.5h for the first 2h. The samples were analysed for VSS, SCOD, PO_4-P and NO_3-N. Phosphate release and denitrification rates were calculated after 2h and 1.5h, respectively. Replicates of the P release and denitrification tests were not completed because the wastewater and RAS needed to be used within 1-2 hours after collection. Therefore the 4 series of experiments were completed in batches and results compared [20].

2.4 Analytical methods

The samples were centrifuged at 8804×*g* for 20 min (Hettich Zentrifugen, Tuttlingen, Germany) and the supernatant filtered through a 0.45 µm (glass-fiber filter paper) prior to analyses. Chemical oxygen demand, NO_3-N, NH_4^+, PO_4-P were determined using Merck Spectroquant cell test (Darmstadt, Denmark) according to the manufacturer instructions. Solids determination, TSS and VSS, was performed according to Standard Methods [21]. All the analyses were completed in duplicate.

For VFAs determination, 9 ml of the filtrate was placed in 10 ml plastic tubes and acidified with 10 µl of sulphuric acid (98% purity) and frozen until high performance liquid chromatography (HPLC) analyses was completed. The VFAs samples were analysed in triplicate using a HPLC (Shimadzu VP Series, Shimadzu, Milton Keynes, UK) with the ultraviolet (UV) detector set at 208 nm. The columns Biorad (cat. 125-0115) (105 mm × 7.8 mm) and the guard column (Biorad cat. 125-0131) were maintained at 65°C. The injection volume was 15 µl and each sample was run for 0.5h using 1 mM sulphuric acid pumped at a flow rate of 0.8 ml min^{-1}. A mixture of VFAs (acetic acid, propionic acid, butyric acid and valeric acid analytical grade) at concentrations between 0.05 - 1 g l^{-1} was used as internal standard.

3. Results and discussion

3.1 Soluble COD and VFAs production

Soluble COD and VFAs concentrations of SAS increased to 3.6 g l^{-1} and 0.37 g l^{-1} after mechanical disintegration by a deflaker corresponding to a 9 fold and 4.1 fold increases from initial values, respectively (Table 2). The primary sludge was fermented during 80h and after this period the SCOD increased to a maximum value of 10.3 g l^{-1} (Site 5) with an average SCOD increase of 2 fold for all sources of primary sludge fermented (Table 2). Likewise, the VFAs concentration increased to an average value of 6.5 g l^{-1} with the highest VFAs production observed for the sludge from Site

5 with a final concentration of 8.7 g l^{-1}. The maximum increase in VFAs was 2.5 fold from the initial concentration (Table 2).

The VFAs and SCOD production yields from SAS disintegration were 6 g VFAs kg^{-1} TSS and 62 g SCOD kg^{-1} TSS. In comparison, the yields from primary sludge fermentation were 81 g VFAs kg^{-1} TSS and 95 g SCOD kg^{-1} TSS. The SCOD and VFAs yields indicate that primary sludge fermentation promoted VFAs production while SAS disintegration mainly induced SCOD release. Full-scale static primary sludge fermenter thickeners have yields of 25-40 g VFAs kg^{-1} sludge after 2-3 days [9], which are in the same order of magnitude of the yields described here.

For all types of sludge fermented (Sites 1 to 5) and disintegrated SAS the production of VFAs was found to be linearly correlated with SCOD release (Fig. 1). The correlation factors (R^2) were calculated over the 80h fermentation period and the values recorded were between 0.99 (Site 2) and 0.86 (Site 5) and therefore can be considered linearly correlated. Hence, VFAs were the main SCOD constituent during fermentation independent of the initial sludge initial characteristics. Fermentation of sludge is described the happen through hydrolysis of complex organic matter into soluble organic compounds that are transformed into volatile fatty acids during acidogenesis. Between 69-94% of the SCOD generated during primary sludge fermentation from sites 1-5 were VFAs (Table 2, Fig.1). Others have reported a proportion of 85% VFAs [5]. Comparatively, only approximately 12% of the SCOD released during SAS disintegration were VFAs. In a previous study it was demonstrated that the SCOD released during SAS disintegration was composed of proteins (30%), carbohydrates (13%) and VFAs (12%) but the remaining 45% of the SCOD was not characterised [16]. Other studies have also identified SCOD as the main product [22] that could be fractionated into proteins, extracellular polymeric substances and soluble microbial products after ultrasound [23, 24] or thermal treatment [25], but the identification of the complete range of substances that contribute to SCOD has not yet been described.

Mainly acetic acid (41%) and propionic acid (36%) were produced during primary sludge fermentation for Sites 1, 2 and 3 with an acetic acid production of 47-62 g kg^{-1} TSS (Fig. 2). Other authors have observed equivalent VFAs production after fermentation of primary sludge at 20°C with 43% of acetic acid and 41% of propionic acid [19]. VFAs production was observed to predominantly occur during the first 40h of primary sludge fermentation with rates between 0.118 g VFAs h^{-1} (Site 1) to 0.188 g VFAs h^{-1} (Site 5). Between 46h and 80h, fermentation processes occurred at a lower rate and the VFAs formation rates decreased to values of 0.03 g VFAs h^{-1} (Site 1). On the other hand, SAS disintegration mainly produced acetic acid (90%) and propionic acid (10%) (Fig. 2).

3.2 Nutrient removal predictive tests

Nutrient predictive tests can be used to estimate the BNR performance using a specific carbon source [20]. These tests are based on the PO_4-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 (3.5 mg l^{-1}) and SCOD (50 mg l^{-1}) concentration with the aim of assessing separately the influence of SCOD and VFAs on P and N removal. The nutrient removal tests were done in parallel using the same source of wastewater implying the same microbial community as inoculum and only parameter that was changed was the carbon source. Therefore it should be possible to compare the impact of the different carbon sources on the nutrient removal rates.

When the carbon addition was matched in total VFAs concentration, the highest P release rates were obtained for the disintegrated SAS supernatant and disintegrated SAS with values of 0.026 and 0.025 mg PO_4-P g^{-1} VSS min^{-1}, respectively (Fig. 3a). Comparable results were obtained in the denitrification tests with the highest denitrification rates measured for the SAS disintegrated sludge and supernatant 0.039 and 0.036 mg NO_3-N g^{-1} VSS min^{-1}, respectively (Fig. 4a).When the carbon

addition was matched in terms of SCOD the highest phosphorus release rate was obtained for disintegrated SAS (0.031 mg PO_4-P g^{-1} VSS min^{-1}) and the lowest for acetate (0.024 mg PO_4-P g^{-1} VSS min^{-1}) (Fig. 3a). The denitrification tests showed the same trend with rates of 0.038, 0.040 and 0.039 mg NO_3-N g^{-1} VSS min^{-1} for disintegrated SAS, disintegrated SAS supernatant and fermented primary sludge, and the lowest rate for acetate with 0.027 mg NO_3-N g^{-1} VSS min^{-1} (Fig. 4a). From the nutrient predictive tests it can be established that the carbon obtained from the sludge was more suitable for BNR (phosphate release and denitrification) than the external acetate carbon source because primary sludge fermentation and disintegrated SAS gave higher phosphate releases and denitrification rates. This observation is supported by Fig. 3b and 4b that show phosphate releases and denitrification rates above the values in the control and acetate vessels (baseline). Furthermore, the denitrifying bacteria seem to be able to use a wider range carbon sources as identified through the comparison of rates when the carbon was matched in total VFAs and SCOD (Figure 4b). Denitrification metabolism is favoured over phosphate release because denitrifying bacteria compete over readily available carbon sources with PAOs and can use wider type of carbon [26]. The denitrification rates recorded (1.4-1.9 mg NO_3-N g^{-1} VSS h^{-1}**)** were similar to those obtained with ozonated SAS as a carbon source [29] (Table 3). Denitrification rates have been demonstrated to be dependent on the biomass concentration [30] but also the origin of the biological material and its activity [31] which could possibly explain the high rates obtain in other studies that varied between 7-41 mg NO_3-N g^{-1} VSS h^{-1} (Table 3). This emphasizes that denitrification tests should be completed for a specific wastewater/carbon source and compared with a control using the same source of denitrifying bacteria [20]. Treatment of ammonia and nitrate in anaerobic conditions has also been demonstrated by using enriched cultures of ANAMMOX (anaerobic ammonium oxidation bacteria) [27].

The phosphorus release rates (0.9-1.5 mg PO_4-P g^{-1} VSS h^{-1}) determined for the internal carbon sources were in the same range of reported rates, between 1.3-2.5 mg PO_4-P g^{-1} VSS h^{-1} (Table 3). The PAOs responsible for phosphate release, were more selective with regard to carbon source use as was demonstrated by differences in the PO_4-P release rates when the carbon source was matched in total VFAs in comparison with SCOD (up to 0.01 mg PO_4-P g^{-1} VSS min^{-1} higher when matched in total VFAs) (Fig. 3b). The internal carbon sources not only contained VFAs, but also other substances that contributed to the SCOD. The SCOD of the wastewater after internal carbon addition matched on VFAs was on average 63 mg l^{-1} (fermented primary sludge addition) and 91 mg l^{-1} for the disintegrated SAS in comparison with 50 mg l^{-1} in the vessel supplemented with acetate. Hence, the microbial species that complete phosphate release not only use VFAs but also other sources of soluble carbon [20]. Adaptation of the biomass to the carbon source could further enhance the phosphorus release rates to 5.9 mg PO_4-P g^{-1} VSS h^{-1} as it has been demonstrated by Puig et al. [28].

3.3 Carbon to nutrient ratios

The fermented primary sludge and the disintegrated sludge were further compared by calculating the carbon to phosphorus (SCOD:PO_4-$P_{release}$) and carbon to nitrate (SCOD: NO_3-N) ratios which can be used to estimate the BNR potential of a specific wastewater/carbon source [2] (Table 3). The SCOD:PO_4-$P_{release}$ ratio varied between 8:1 for disintegrated SAS and 15:1 for acetate and the SCOD:NO_3-N ratio ranged between 9:1 and 12:1 (Table 3). Both SCOD:PO_4-$P_{release}$ and SCOD: NO_3-N ratios indicate that the most effective carbon source for BNR was disintegrated SAS. A substantial difference between SCOD:PO_4-$P_{release}$ for disintegrated SAS and fermented primary sludge with values of 8 and 15, respectively, was observed. As previously described, nutrient release with disintegrated SAS was not enhanced by the presence of viable PAOs after disintegration [20]. The difference between SCOD:PO_4-$P_{release}$ ratio recorded for the SAS and primary sludge carbon sources was likely to be linked to the type of carbon and bioavailability. The

main SCOD component of fermented primary sludge was VFAs corresponding to 90% of the SCOD and this type of carbon source has been extensively studied for BNR enhancement [2, 7, 8]. Yet the SCOD products of SAS disintegration have not been completely identified since only approximately 12% were VFAs with 45% of the SCOD remaining uncharacterised [16]. Further work needs to be completed to identify the products of the SAS disintegration that enhance BNR (P release and NO_3^- reduction) at rates above acetate and fermented primary sludge (Table 3).

3.4 Implications of using primary sludge fermentation and SAS disintegration as carbon sources to the sewage treatment works

The disintegration of SAS was observed to enhance NH_4^+ and PO_4-P concentrations from 10 mg NH_4^+ l^{-1} and 159 mg PO_4-P l^{-1} to 60 mg NH_4^+ $l^{-1}$and 500 mg PO_4-P l^{-1}, respectively, i.e. the nutrients increased by a factor of 6 (NH_4^+) and 3.5 (PO_4-P) (Table 2). The SAS disintegration promoted higher phosphate release than sludge fermentation since this nutrient is removed from the wastewater by accumulation in the biomass [32] and it was solubilised during the disintegration process. The NH_4^+ and PO_4-P concentrations were also observed to increase during the fermentation period (Table 2) and a strong correlation was observed between acetic acid production with both ammonia (correlation factors R^2 from 0.73 to 0.96) and phosphorus release (correlation factors R^2 from 0.88 to 0.94). On average, the PO_4-P and NH_4^+ release from the fermentation of primary sludge was 2.1 and 4 fold higher than the initial concentration of 18.3 mg PO_4-P l^{-1} and 111.9 mg NH_4^+ l^{-1}.

The implications of using primary sludge fermentation and SAS disintegration as carbon source were assessed by completing a nutrient mass balance to a full-scale BNR treatment works treating 10,000 m^3 day^{-1} of wastewater (Table 4). The volumes of fermented primary sludge and disintegrated SAS added to the BNR settled sewage were calculated based on predictive tests match on SCOD (fermented primary sludge 4.2 ml in 2 l of wastewater and disintegrated SAS 13 ml in 2 l of wastewater) with dilution factors of 0.0021 and 0.0065 in the wastewater, respectively. The

addition of fermented sludge would increase the ammonia load by 13 kg day^{-1} and PO_4-P by 2 kg day^{-1} in the settled sewage fed to the BNR process. The addition of disintegrated SAS was likely to increase the PO_4-P in the settled sewage feeding the BNR process by an additional load of 33 kg day^{-1}.

The ratios of nutrient recycled to the BNR versus SCOD feed to the process indicate that the use of disintegrated SAS as internal carbon source could lead to a cycling of phosphorus in the STW with 0.97 g PO_4-P kg^{-1} SCOD. Ammonia concentrations would also be increased (0.11 g NH_4^+ kg^{-1} SCOD) but to a lesser extent than for phosphorus (Table 4). The addition of primary sludge fermentation products for enhancing the BNR process is recommended since the recycling of nutrients would be minimised (0.02 g PO_4-P kg^{-1} SCOD and 0.13 g NH_4^+ kg^{-1} SCOD). For the SAS disintegration product to be a suitable carbon source for BNR and complement the beneficial carbon to nutrient ratios here described, the phosphorus would potentially need to be removed from the disintegration liquors. Phosphate removal could be achieved using chemical precipitation with iron sulphate or alum or alternatively, struvite ($MgNH_4PO_4.6H_2O$) formation could be promoted by providing suitable conditions for its precipitation (pH 8.5 and a ratio of 1:1:1 of phosphate:ammonia: magnesium) with 80% phosphate recovery [33]. In addition, an economical evaluation has demonstrated that sludge disintegration using a deflaker is an energy intensive process (6138 kW day^{-1} in a 50,000 m^3 day^{-1} treatment works) [20] in comparison with sludge fermentation with virtually no operational costs associated [9].

4. Conclusions

The fermentation of primary sludge promotes VFAs production as 69-94% of the SCOD generated consisted of VFAs, compared with approximately 12% VFAs in the SCOD released during SAS disintegration. Higher VFAs yields were observed during the first 40h of fermentation.

The nutrient removal tests demonstrated that internal carbon sources obtained from sewage sludge enhanced phosphate release and denitrification compared with acetate. The disintegrated SAS was the more suitable carbon source for BNR compared with fermented primary sludge (SCOD:PO_4-$P_{release}$ ratio of 8 and SCOD:NO_3 ratio of 9) since other components contributing to SCOD besides VFAs promoted BNR. Further work should be completed to identify these products of SAS disintegration. However for disintegrated SAS to be considered a suitable carbon source for BNR the PO_4-P would potentially need to be removed before recycling to the BNR wastewater. Overall the addition of primary sludge fermentation products for enhancing the BNR process is recommended since the recycling of nutrients would be minimised (0.02 g PO_4-P kg^{-1} SCOD and 0.13 g NH_4^+ kg^{-1} SCOD).

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Figures captions:

Fig. 1. Correlation between SCOD and VFAs content in COD equivalent (VFAs-COD, calculated according to Lie and Welander [38] 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 (○), Site 5 (×) and SAS sludge (●). The correlation coefficients (R^2) for the curves varied between 0.86 for Site 4 and 0.99 for Site 2.

Fig. 2. VFAs concentrations after 80 hours of fermenting the primary sludge collected from 5 different full-scale sites and after mechanical disintegrating SAS originated from a pilot-scale BNR reactor with a deflaker: acetic acid (□), propionic acid (■), butyric acid (▤) and valeric acid (▥). The error bars show the standard deviation of the duplicate fermenters.

Fig. 3. a - Phosphorus release rate when the carbon addition was matched in total VFAs (□)and SCOD (■) in the control vessel with no addition of carbon source (1); with acetate (2); with fermented primary sludge from Site 1 (3), with disintegrated SAS (4) and with disintegrated SAS supernatant (5). b – Calculated phosphorus release rate above control vessel (with no addition of carbon source) and acetate supplemented vessels.

Fig. 4. a - Denitrification rate when the carbon addition was matched in total VFAs (□) and SCOD (■) in the control vessel with no addition of carbon source (1); with acetate (2); with fermented primary sludge from Site 1 (3), with disintegrated SAS (4) and with disintegrated SAS supernatant (5). b – Calculated denitrification rate above control vessel (with no addition of carbon source) and acetate supplemented vessels.

Table 1. Carbon added to the phosphorus release test and denitrification test when the carbon source was matched in SCOD or VFAs.

	Carbon match (mg l^{-1})	**Initial SCOD (mg l^{-1})**	**Vessel 1 (Control)**	**Vessel 2 (Acetate) (ml)**	**Vessel 3 Primary sludge supernatant (ml)**	**Vessel 4 Disinteg. SAS (ml)**	**Vessel 5 Disinteg. SAS supernatant (ml)**
P test	VFAs: 3.5	50	-	2.5	7.4	25.0	25.0
	SCOD: 50	40	-	5.0	4.2	12.0	13.0
N test	VFAs: 3.5	49		1.2	3.6	32.0	32.0
	SCOD: 50	34		5.8	4.9	15.0	15.0

Table 2. Primary sludge and SAS composition before and after 80h fermentation at 20°C and disintegration with deflaker.

	Before fermentation				After fermentation			
Primary sludge	**SCOD ($g\ l^{-1}$)**	**NH_4 ($mg\ l^{-1}$)**	**P ($mg\ l^{-1}$)**	**VFAs ($g\ l^{-1}$)**	**SCOD ($g\ l^{-1}$)**	**NH_4 ($mg\ l^{-1}$)**	**P ($mg\ l^{-1}$)**	**VFAs ($g\ l^{-1}$)**
Site 1	5.6	187.0	50.3	2.2	10.2	598.0	87.5	6.3
Site 2	4.8	70.2	3.5	3.3	7.5	543.0	6.6	5.2
Site 3	2.3	128.0	10.7	2.9	7.8	307.7	22.8	4.6
Site 4	4.0	70.2	23.5	2.4	7.5	300.0	42.5	5.4
Site 5	4.1	104.0	3.5	3.5	10.3	200.0	11.6	8.7
SAS	**Before disintegration**				**After disintegration**			
Pilot-scale BNR	0.4	10.0	159.0	0.09	3.6	60.0	500.0	0.37

The standard deviation obtained for the duplicate fermentations was: 0.5 $g\ l^{-1}$ for SCOD; 3.0 $mg\ l^{-1}$ for NH_4^+; 1.0 $mg\ l^{-1}$ P and 0.5 $g\ l^{-1}$ for VFAs.

Table 3. Carbon to nutrient ratios and phosphorus release rates and denitrification rates over a range of internal and external carbon sources.

	PO_4-P			NO_3-N		
Carbon source	**SCOD: PO_4-P**	**mg PO_4-P g^{-1} VSS h^{-1}**	**Reference**	**SCOD: NO_3-N**	**mg NO_3-N g^{-1} VSS h^{-1}**	**Reference**
Acetate	15.0	0.5	This study	9.0	0.9	This study
Fermented primary sludge	15.0	0.9	This study	10.0	1.4	This study
Disinteg. SAS	8.0	1.5	This study	9.0	1.9	This study
Disinteg. SAS supernatant*	9.0	1.4	This study	12.0	1.6	This study
Various substrates	4.9-10.0		[34]			
Acetate (30 adapted)		5.9	[28]			
Ethanol (non-adapted)**		1.5	[28]			
Hydrolysed primary sludge					41.0	[35]
Mechanically disintegrated SAS					15.0	[36]
Ozonated SAS					0.5-3.4	[29]
Sucrose (biomass in immobilised filter)				2.5		[30]
Acetate				10.0		[37]
Acetate		1.3	[20]		7.0	[20]
Disintegrated SAS		2.5	[20]		15.0	[20]

*** Disintegrated SAS supernatant was obtained after centrifuging disintegrated SAS and therefore it was mainly composed of soluble products.**

****Microbial community used was not pre-adapted to ethanol as single carbon source**

Table 4. Phosphate and ammonia mass balance on a BNR treatment plant with a capacity of 10,000 m^3 day^{-1} after addition of fermented primary sludge or disintegrated SAS supernatant.

		Primary sludge supernatant	Disinteg. SAS supernatant
Dilution factor calculated from the nutrient removal predictive tests		0.0021 (4.2 ml in 2 l of wastewater)	0.0065 (13.0 ml in 2 l of wastewater)
Nutrients in the sludge	PO_4-P (mg l^{-1})	87	500
	NH_4^+ (mg l^{-1})	598	60
Increased nutrient load to the BNR process	PO_4-P (kg day^{-1})	2	33
	NH_4^+ (kg day^{-1})	13	4
Ratio between nutrient recycled and SCOD	g PO_4-P kg^{-1} SCOD	0.02	0.97
	g NH_4^+ kg^{-1} SCOD	0.13	0.11

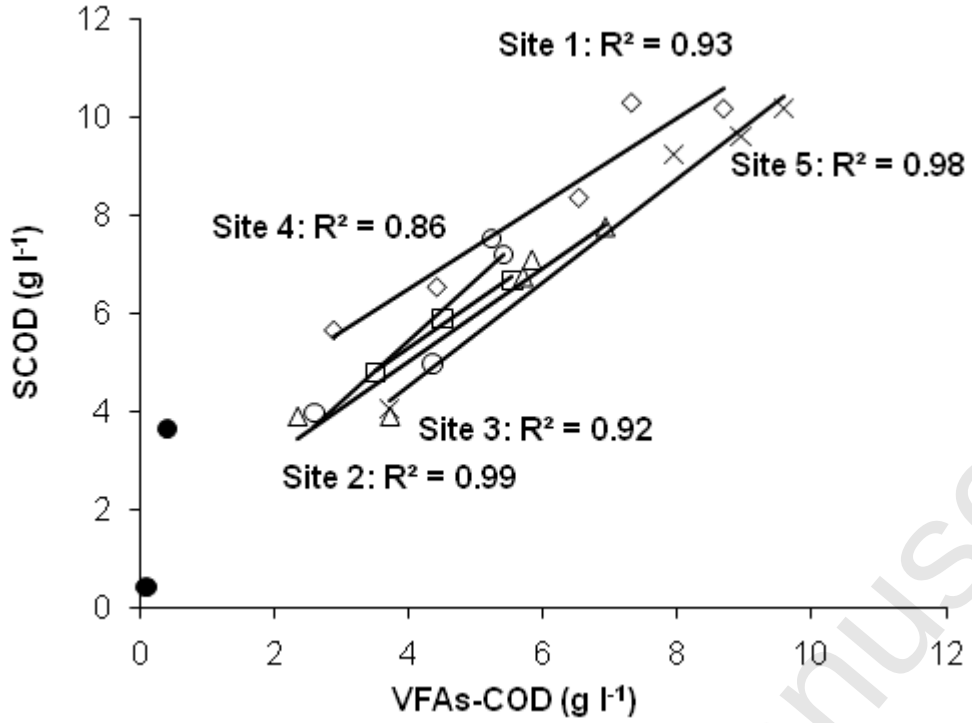


Fig. 1.

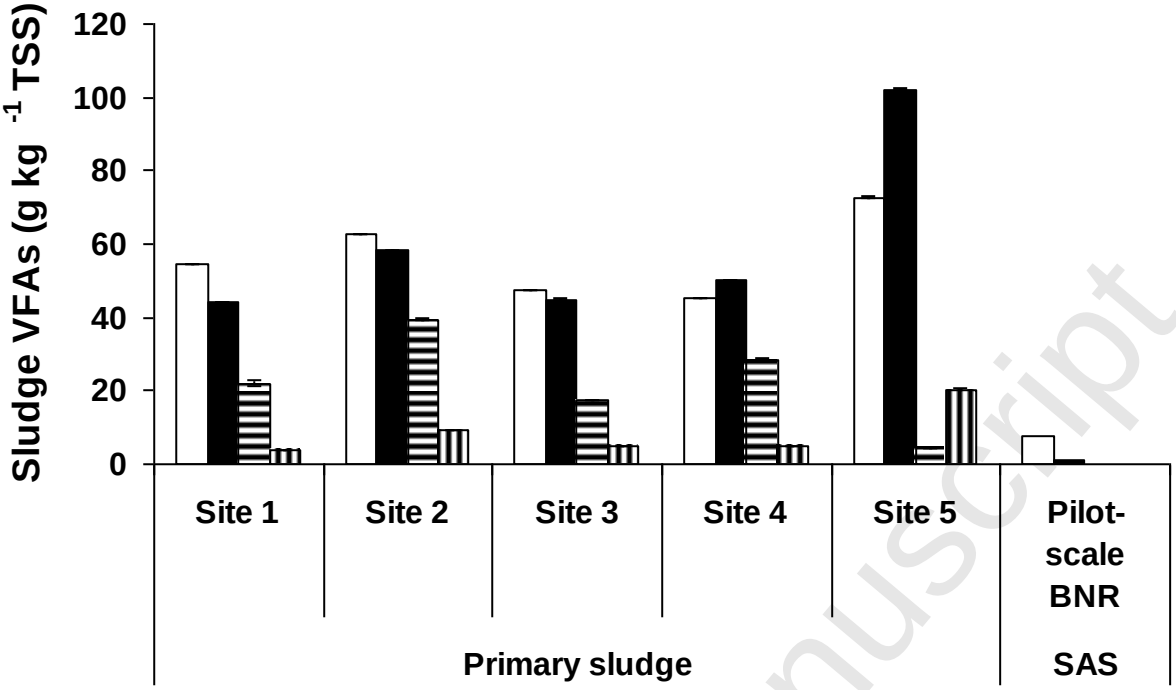
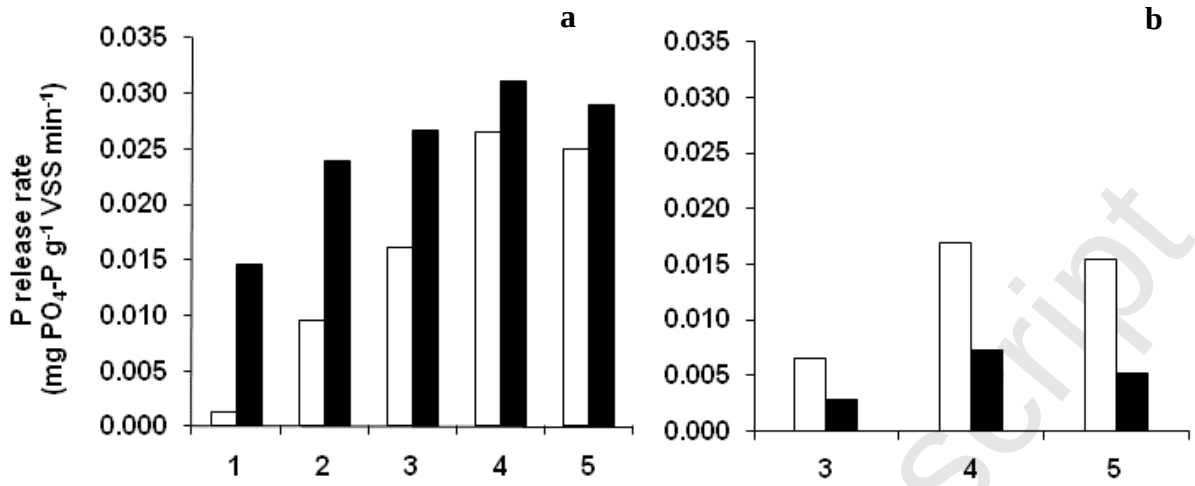


Fig. 2.



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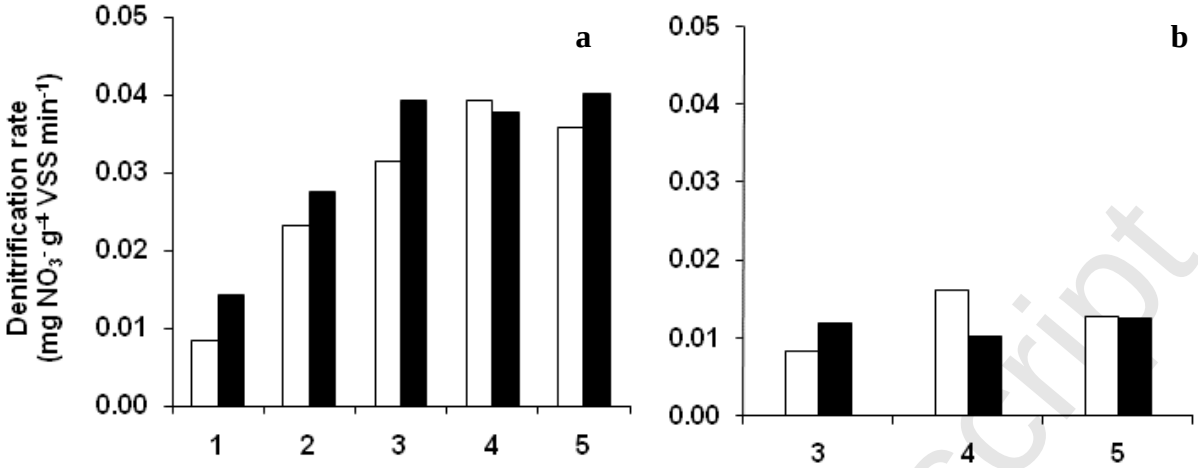

Fig. 4.