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Treatment of sidestream dewatering liquors from thermally hydrolised and anaerobically digested biosolids

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Abstract

A long term operation (22 months) of the sidestream treatment plant at the water and resource recovery facility at the Tilburg sewage works in The Netherlands is presented. This plant treats dewatering reject liquor from thermally hydrolysed (THP) and mesophillic anaerobically digested (MAD) biosolids. The sidestream plant is comprised of a Phospaq struvite reactor for removal and recovery of phosphate and an Anammox reactor for removal of ammoniacal nitrogen. Potential inhibiting characteristics of THP-MAD reject liquor were successfully mitigated by various measures like pre-aeration and addition of dilution water. The sidestream plant demonstrated excellent performance in handling large fluctuations in load and composition, producing effluent with stable low NH_4 and BOD concentrations achieving removal efficiencies up to 90% on both NH_4 and BOD.

Key words: anaerobic digestion, anammox, sidestream treatment, struvite, thermal hydrolysis (THP)

INTRODUCTION

Waterboard De Dommel operates 8 wastewater treatment plants (WWTP) with a total capacity of 1.5 million population equivalent (1 PE equal to 150 g COD) in the south-eastern part of the Netherlands (Van Veldhoven *et al.* 2018). Waterboard De Dommel made a strategic decision to build a water and resource recovery facility (WRRF) at Tilburg WWTP to process all biosolids generated by the eight WWTPs. The sludge from the various sites comprises primary as well as secondary activated sludge. The main objectives of this project were decreasing operating cost for sludge handling, maximizing energy production (biogas) and the possible recovery of phosphorus. The overall WRRF project involved the supply, modification and installation of:

- Thermal sludge hydrolysis plant (Cambi THP – 165 °C – 29,500 tds/yr);
- Anaerobic digestion (3 × 4,400 m^3 – 25,500 tds/yr)
- Sludge dewatering equipment (centrifuges)
- Sidestream treatment plant (Phospaq-Anammox – 1,850 kgNH_4-N/d and 240 kgP/d).

The WRRF has been fully operational since the end of 2017 while the sidestream treatment plant has been treating all sludge dewatering reject liquors generated. The main uncertainty was formed by the potential inhibiting effects of compounds in the THP-MAD reject liquor.

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At full capacity, the dewatering reject liquors from the sludge centre would make up a substantial part (up to 45%) of the total nitrogen load to the Tilburg main sewage works. Hence, sidestream treatment of the reject water from the sludge dewatering was required to reduce the nitrogen load to the main works of Tilburg WWTP. The projected sidestream treatment plant was designed to reduce the nitrogen load returned to the mainstream Tilburg WWTP to a maximum of 450 kg N-total/d.

METHODS

The sidestream plant comprises a 500 m^3 PHOSPAQ struvite reactor for removal and recovery of phosphorus and an 1,100 m^3 ANAMMOX reactor for the energy efficient removal of ammoniacal nitrogen. Treatment with combined Phospaq-Anammox was first applied by the company Waterstromen at WWTP Olburgen, in Netherlands in 2006, treating MAD reject liquors and industrial effluent. (Abma *et al.* 2010).

The Phospaq is an aerated reactor system designed for the simultaneous removal of BOD and phosphate. Phosphate is recovered by controlled precipitation of struvite (magnesium-ammonium-phosphate), producing a slow release fertiliser. While the Phospaq reactor is aerated to keep the struvite crystals in suspension, BOD is oxidized simultaneously. The Phospaq reactor is equipped with a special medium-coarse bubble aeration system to maximize agitation but minimize any scaling. A dedicated separator is installed within the reactor to retain the well settleable struvite crystals formed. Struvite is harvested and subsequently dewatered by a screw press and finally collected in bulk containers. The Phospaq reactor acts as a peak shaving unit in case of excessive release of BOD5, mitigating any adverse effects to the downstream process. Lamella clarifiers were incorporated in the original design to remove any elevated amounts of solids and meet discharge requirements. Since 2006 a total of 11 Phospaq reactors have been built with a total installed treatment capacity of 4,940 kg P/d (Driessen *et al.* 2018a).

The installed Anammox reactor is a single stage partial nitritation/anammox system using granular biomass. The Anammox reactor is typically continuously aerated and equipped with a specially designed biomass separator to ensure selective retention of the granular biomass. Since the installation of the first Anammox reactor in 2002 at Dokhaven in Rotterdam (Netherlands), 62 full-scale Anammox plants have been built with a total installed treatment capacity of 139,000 kg N/d. Figure 1 depicts the Tilburg water and resource recovery facility.

Although micronutrients are generally sufficiently available in digested sewage sludge reject liquors, fulvic and humic-like organic substances generated by the THP process are known for binding

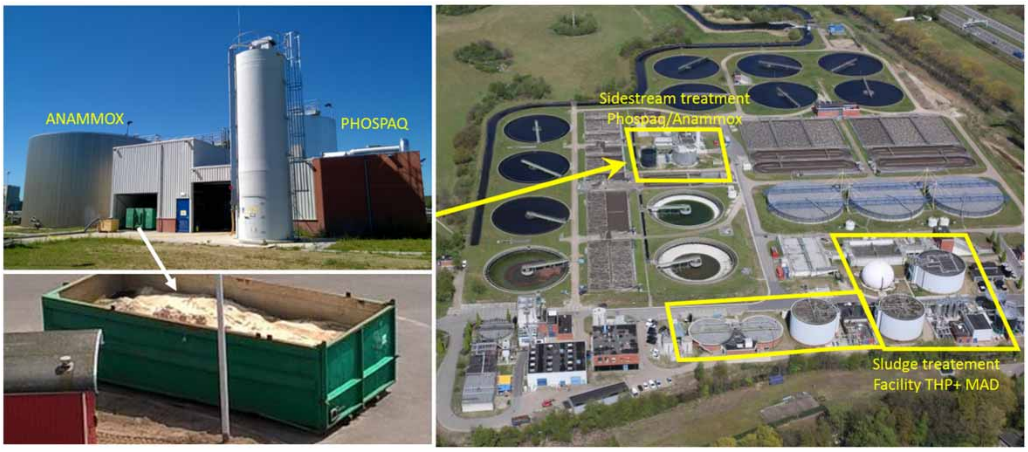

Figure 1 | Pictures of sidestream treatment plant comprising Phospaq and Anammox reactor and the sludge treatment facility comprising THP and MAD at the centralised sludge treatment plant at Tilburg (derived from Driessen *et al.* 2018b).

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metal-ions, possibly reducing the bioavailability of essential trace elements. To ensure optimal biological activity and growth of the biomass micronutrients (essential trace metals) are dosed to the Anammox reactor.

Figure 2 presents a schematic flow diagram of the sidestream treatment plant. The centrate to the sidestream plant was composed of approximately 80% post THP-MAD sludge dewatering reject liquor and 20% pre-THP reject liquor. The design did allow for addition of dilution water to mitigate for any possible inhibiting effects on the biological process caused by substances present in the THP-MAD reject liquor (Zhang *et al.* 2018). The dilution water used was heated up by excess heat derived from the THP external heat exchangers. The sidestream plant is normally operated at temperatures of around 30–35 °C (average 32 °C). Under steady state conditions, the Anammox reactor is typically operated at pH 6.8 ($\pm$0.2).

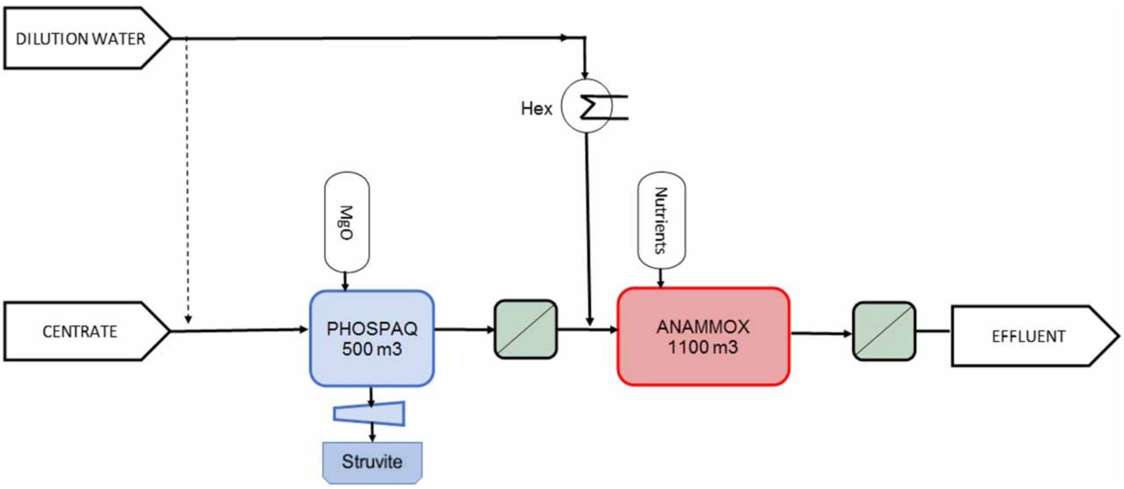

Figure 2 | Schematic flow diagram of the sidestream liquor treatment plant at Tilburg comprising a Phospaq struvite reactor and Anammox reactor.

RESULTS AND DISCUSSIONS

During the initial start-up of the WRRF, several significant operational problems were encountered; for example, excessive release of solids and COD, overdosing of dewatering polymer, foaming and scaling of piping (Van Veldhoven *et al.* 2018). During such extreme conditions, solids concentrations in the centrate were sometimes as high as 5 gTSS/L. Optimisation of the operation of the sludge dewatering centrifuges as well as the use of bespoke dewatering polymers has significantly reduced the solids loading (TSS <1 g/L). The remaining TSS still entering the sidestream plant was generally of a fine and colloidal nature.

Excessive foaming, often related to high influx of solids and polymer, was resolved after optimisation of the sludge dewatering operation and change in type of polymer (Van Veldhoven *et al.* 2018). Dosing antifoaming agent has been applied successfully to control any residual foaming. As the sidestream liquor treatment plant is built remotely (>100 m) from the sludge dewatering unit, the interconnecting piping transporting the raw centrate showed initial signs of scaling (struvite). This problem was resolved by dosing an anti-scaling agent.

The amount of centrate produced varied between 200 and 1,200 m^3/d. Dilution water was continuously provided at an initial average reject-water/dilution-water ratio of about 1:1. Since the last 8 months, the dilution ratio has been decreased to approximately 1:0.5 without any noticeable adverse effect on performance of the deammonification process in the Anammox reactor.

Figures 3 and 4 present the concentrations of COD, BOD5, NH_4 and PO_4 of the sidestream reject liquor. As the capacity of the THP process was steadily ramped up, COD, BOD5, NH_4 and PO_4

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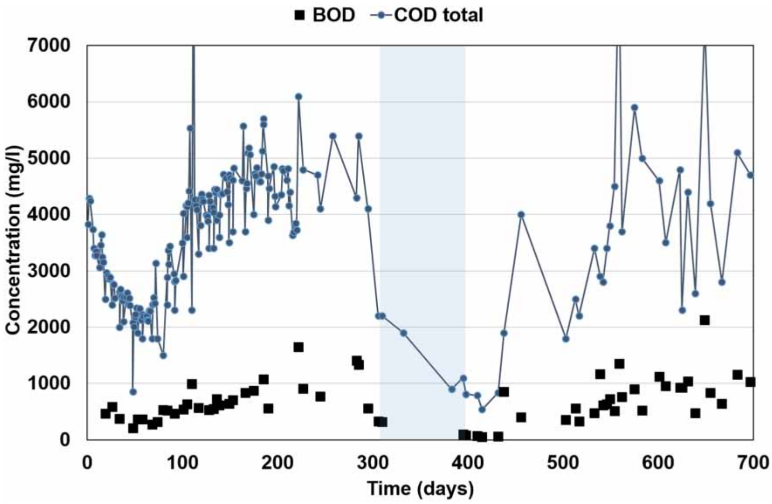

Figure 3 | Concentrations of BOD5 and total-COD.

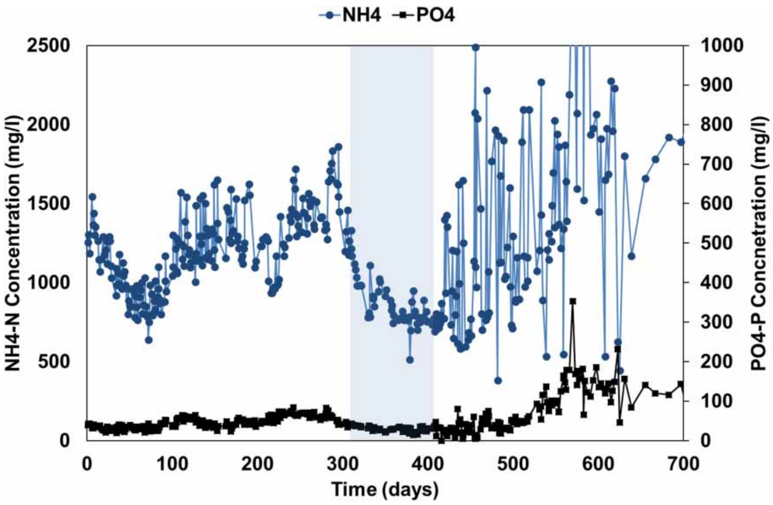

Figure 4 | NH_4-N and PO_4-P in the dewatering reject liquor.

concentrations in the reject liquor gradually increased resulting in more elevated loadings to the sidestream treatment plant. COD, BOD5, NH_4-N and PO_4-P concentrations increased up to 5,000 mg/L, 800 mg/L, 1,600 mg/L and 75 mg/L respectively. After day number 300, the load to the sidestream plant was reduced gradually as the THP plant was shut down for maintenance and because of diversion of some sludge streams. During this low loading period (day 300 until day 400), COD, BOD5, NH_4 and PO_4 inlet concentrations were reduced to around 1,650 mg/L, 250 mg/L, 900 mg/L and 30 mg/L respectively. Since day number 400, the loading rate did increase again as the THP plant was operated with an increasing amount of biosolids. As a result, since this day, COD, BOD5, NH_4 and PO_4 inlet concentrations increased again to around 4,500 mg/L, 950 mg/L, 1,900 mg/L and 120 mg/L respectively.

COD AND BOD5

Figure 5 presents the COD to and from the sidestream plant. At full operation of the THP, the COD load to the sidestream plant increased to 4,000–5,000 kg/d while COD in the outlet reached around 1,500–2,100 kg/d. Figure 6 demonstrates high performance on BOD5 removal while the BOD5 load

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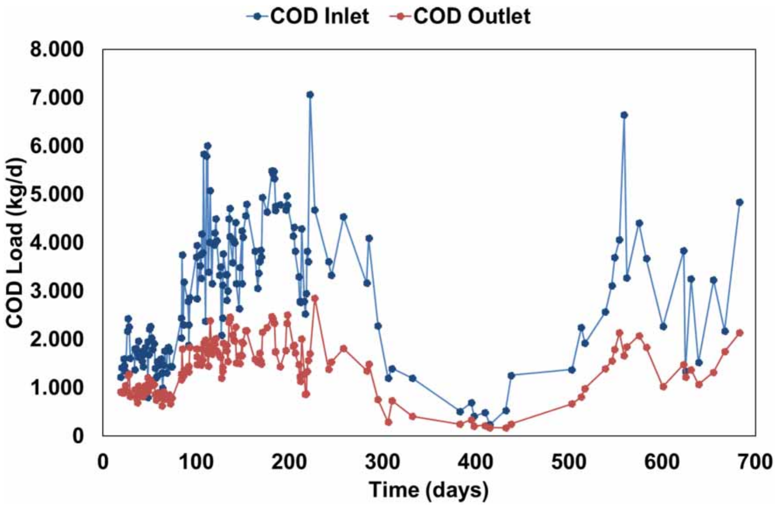

Figure 5 | COD load of inlet and outlet of sidestream plant.

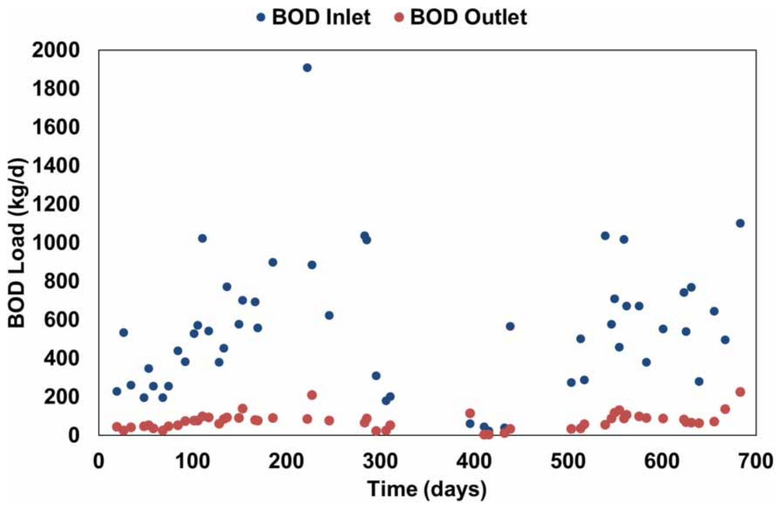

Figure 6 | BOD5 load of inlet and outlet sidestream plant.

in the outlet was almost always less than 100 kg/d despite fluctuating inlet BOD5 loads up to 1,000 kg/d (peak 1,910 kg/d). A significant part of this BOD was removed in the Phospaq reactor.

Phosphate

Until day number 500, the average PO_4-P concentration in the reject water was only 43 mgPO_4-P/l (Figure 4). As a result, the PO_4-P load was around 40 kgPO_4-P/d (range 20–75 kgPO_4-P/d), which was much lower than the design value of 240 kg PO_4-P/d. It was only after day number 550 that the PO_4-P load did gradually increase to about 100–120 kg/d. Because of the relatively low PO4 concentrations, struvite production has been limited accordingly.

A reason for the actual PO_4-P load being much lower than the design load is the dosing of ferric chloride ($FeCl_3$) to the anaerobic digesters. In the anaerobic digesters, ferric iron (Fe^{3+}) is converted into ferrous iron (Fe^{2+}), which reacts with HPO_4^{2-} to form vivianite [$Fe_3(PO_4)_2 \cdot 8(H_2O)$] (Wilbert *et al.* 2018). Precipitation deposits taken from the anaerobic digesters were identified as being predominantly vivianite. Another reason for the relatively low PO_4 concentration might be the relatively high fraction of biosolids derived from WWTPs using chemical means over biological processes to remove phosphorus.

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Ammoniacal nitrogen

The Anammox reactor was inoculated with batches of granular biomass from various other Anammox plants treating industrial effluent and biosolids dewatering reject liquor. The various batches of biomass seed sludge had different properties in size distribution and color (see first 3 pictures in Figure 7). After 150 days of operation net growth of new biomass was confirmed, resulting in active granules with a typical size of 2–4 mm (see last picture Figure 7).

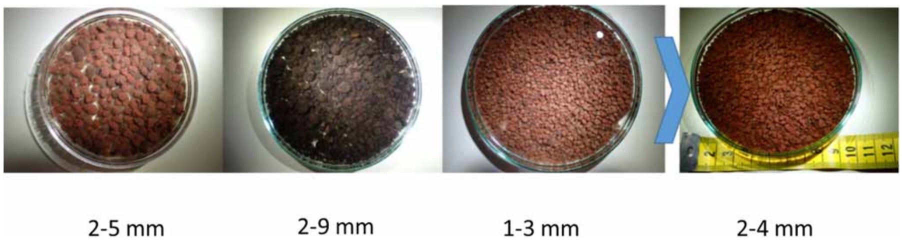

Figure 7 | Three samples of batches of granular biomass used for inoculation (l) and the finally developed granular biomass in the 1-step Anammox reactor after 1 year of operation (r).

As presented in Figure 8, during the first 300 days the NH_4 load increased up to 1,720 kg NH_4-N/d treating all sludge reject liquor produced. The NH_4 removal increased from 65% up to 85%, generally meeting the target return load of less than 450 kg N/d. Between day number 300 and 400, the NH_4 load was much lower at around 400 kg/d only. After day 400, the NH_4 load increased up to 3,800 kgNH_4-N/d, still meeting the return load requirements.

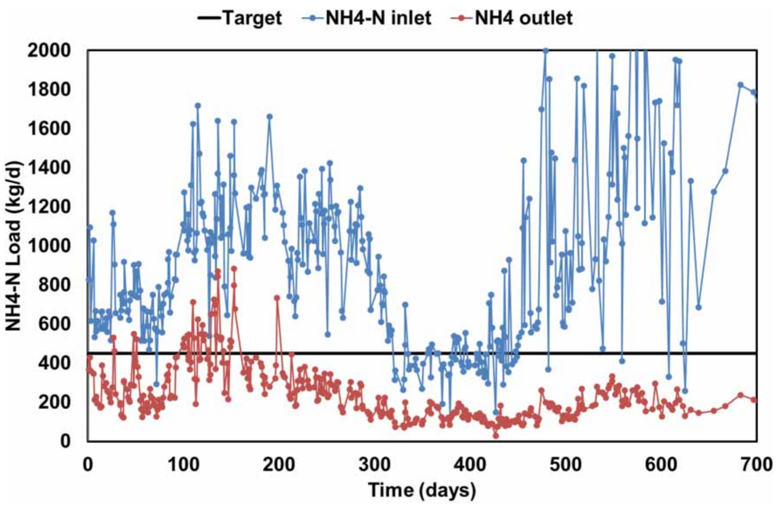

Figure 8 | NH_4-N load of inlet and outlet.

As the NH_4 removal expressed in percentage (%) was often just related to the NH_4 concentration (as mg/L) in the inlet (a higher inlet concentration allows for a higher removal percentage), the NH_4 load (as kg/d) in the outlet of the plant is a more representative performance indicator. The NH_4-N concentration in the outlet remained more or less stable around 140 mg/L on average (typical range 75–250 mg/L) at various loading conditions (Figure 9). The return load at steady state conditions was around 150–250 kg NH_4-N/d (Figure 8).

During the first year, the NH_4 removal efficiency (expressed in percentage) was limited by the amount of alkalinity present in the reject liquor. While converting ammoniacal nitrogen the overall

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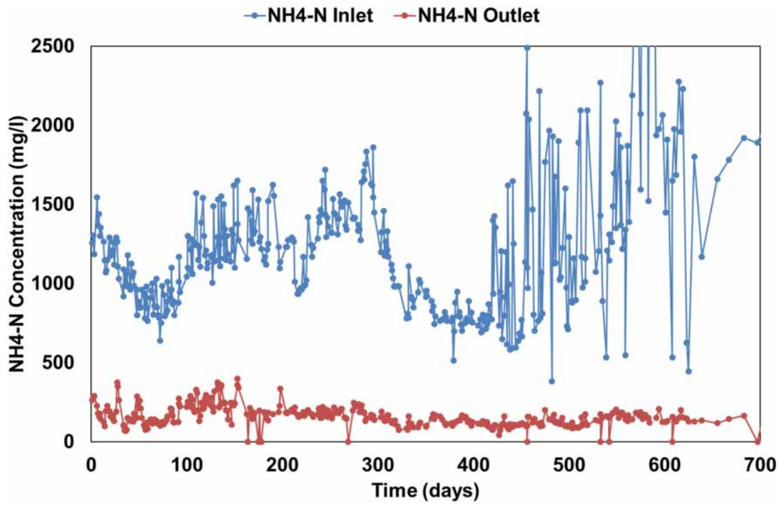

Figure 9 | NH_4-N concentration of the inlet and outlet of the sidestream plant.

process of partial-nitritation-anammox produces H^+ causing pH to drop. Alkalinity present in the reject liquor buffers the pH by absorbing the H^+. For every meq NH_4-N removed, about 1.1 meq H^+ is produced. During the first year, the ratio of alkalinity/NH_4-N (meq/meq) of the reject water gradually decreased from 1.1 to values as low as 0.65, indicating a deficit of alkalinity. The addition of ferric iron (Fe^{3+}) to anaerobic digesters is pointed out to be the main reason for this deficit in alkalinity limiting a more complete biological removal of NH_4^+ by the anammox process (Driessen *et al.* 2018b). Adding alkalinity would have resulted in a higher removal efficiency. Waterboard De Dommel decided not to dose any chemicals to increase the alkalinity as the achieved return load of around 100–250 kgNH_4-N/d was meeting the target effluent load of 450 kgNH_4-N/d. Since day 400, the alkalinity/NH_4-N ratio has increased, allowing even higher NH_4 removal efficiencies of over 90%.

Figure 10 presents the NH_4-N removal as a function of the NH_4-N load in the last 7 months of operation. In this time period, the NH_4 load fluctuated but increased steadily, treating all centrate produced. Figure 10 shows that removal efficiencies were not compromised by higher loadings even up to peaks of 3,800 kg NH_4-N/day (design load 1,850 kg NH_4-N/d). This corresponds to volumetric nitrogen loading rates (NLR) in the Anammox reactor of more than 2.5 kg NH_4-N/m^3.day. The NH_4-N return load in the outlet seemed independent of the applied NH_4-loadings.

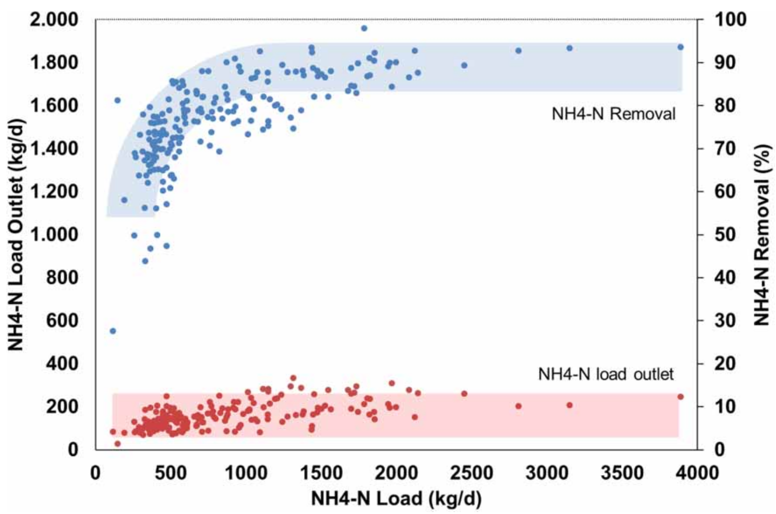

Figure 10 | NH_4-N return load (kg/d) and the NH_4-N removal (%) as function of the NH_4-N inlet load.

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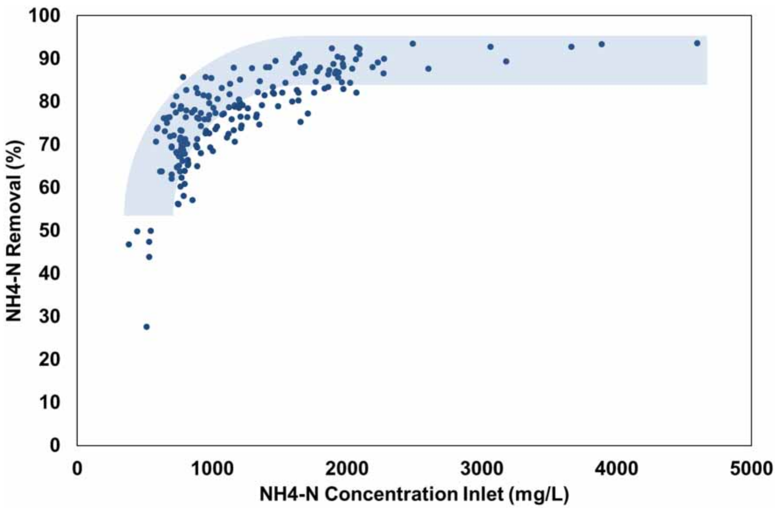

Figure 11 | NH_4-N removal (%) as function of the NH_4-N inlet concentration.

The NH_4 load was mostly a function of the NH_4 concentration in the inlet, hence the lower NH_4 loading at the beginning is predominantly the result of lower NH_4 inlet concentrations. Figure 11 presents the NH_4 removal efficiency as a function of the NH_4 concentration in the raw centrate. The NH_4 removal seems to be related to the NH_4 concentration in the centrate: the higher the inlet concentration the higher the NH_4 removal efficiency.

The anammox reaction is typically associated with approximately 10% production of nitrate (NO_3-N). NO_3-N production exceeding 10–15% of the amount of converted NH_4-N is generally associated with activity of nitrite oxidizing bacteria (NOB). The average effluent nitrate concentration over the whole 700-day period was 42 mgNO_3-N/l (range 4–75 mgNO_3-N/l) only. Although the NO_3-N formation as part of the NH_4-N removed was around 12% at the early start-up, this percentage quickly decreased to stable numbers of less than 5%, indicating NOB activity to be effectively suppressed.

CONCLUSIONS

The combined PHOSPAQ-ANAMMOX sidestream treatment plant was demonstrated to be a resilient solution to treat THP-MAD dewatering reject liquors, producing stable low NH_4 and BOD outlet loadings meeting the discharge requirements at fluctuating loading rates.

After applying methods intended to mitigate possible inhibition from the THP-MAD reject liquor like adding dilution water, removal of BOD and addition of micro-nutrients, no inhibition of the Anammox process was observed.

The ANAMMOX reactor was capable of achieving up to 90% removal efficiency at volumetric nitrogen loadings rates exceeding 2.5 kgNH_4-N/m^3.day. High percentage ammonia removal efficiency was typically related to high ammonia influent concentrations and sufficient alkalinity present in the dewatering reject liquors.

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