WP2 – Nitrogen removal in mainstream

D 2.5: Options for nitrogen removal after advanced carbon extraction

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Deliverable 2.5	*Options for nitrogen removal after advanced carbon extractions*
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Deliverable lead:	Veolia Water Technologies Sweden - AnoxKaldnes
Author(s):	Magnus Christensson, Maria Piculell
Contact for queries	Magnus Christensson (magnus.christensson@anoxkaldnes.com)
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Abstract	Guidelines of process options to remove nitrogen in municipal wastewater after advanced carbon extraction based on results from POWERSTEP deliverables 2.1 – 2.4 and in comparison with conventional processes for resources (energy, footprint, chemicals) and performances (removal, stability, flexibility, sludge production)

Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
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Glossary

AOB	Ammonium Oxidizing Bacteria
AMX-stage	Anammox-stage
AnAOB	Anaerobic Ammonium Oxidizing bacteria (anammox)
COD	Chemical Oxygen Demand
MBBR	Moving Bed Biofilm Reactor
IFAS	Integrated Fixed Film Activated Sludge
NOB	Nitrite Oxidizing bacteria
N-stage	Nitritation-stage
SBR	Sequencing Batch Reactor
WP	Workpackage
WWTP	Wastewater Treatment Plant

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Executive summary

POWERSTEP aims to demonstrate energy-positive wastewater treatment, which requires the utilization of the internal carbon in the wastewater to produce biogas. An increased carbon extraction for biogas production challenges conventional nitrogen removal, in which denitrifying bacteria depend on an easily accessible source of carbon. Hence, POWERSTEP focuses on novel concepts for nitrogen removal in the mainstream line, with a minimum requirement of carbon.

Within work package (WP) 2 of POWERSTEP, *Mainstream nitrogen removal*, three different tasks have been performed that represents three different options for nitrogen removal after advanced carbon extraction.

In task 2.1 *Advanced control strategies*, it was demonstrated in Case study Westewitz WWTP that, with an advanced control system where polymer addition in the primary treatment was based on minimum carbon source requirement for denitrification, a high degree of carbon extraction could be achieved while still meeting the effluent demands for nitrogen, utilizing the conventional nitrification-denitrification pathway.

In task 2.2 *Mainstream deammonification*, the concept using a specific group of autotrophic bacteria, commonly referred to as anammox bacteria, for removal of ammonia to nitrogen gas was demonstrated in full scale prototype in Case study Sjölunda WWTP. Since anammox bacteria are not dependent on carbon for nitrogen removal, the full potential of carbon recovery for biogas production can be reached.

In task 2.3 *Mainstream duckweed reactor*, the potential of using duckweed for high production of vegetal organic biomass for biogas production and simultaneously achieve nitrogen removal, was demonstrated in Case study Westewitz WWTP.

This deliverable provides a guideline, where the different options to remove nitrogen within municipal wastewater after advanced carbon extraction are presented based on the performed tasks in WP2 of POWERSTEP, and in comparison with conventional processes. Special emphasis is made on resources (energy, footprint, chemicals) and performances (removal stability, flexibility, sludge production).

The outcome from POWERSTEP (tasks 2.1.-2.3) and comparisons with conventional processes showed that in order to meet the full potential of carbon recovery and turning the wastewater treatment plant truly energy positive while still meeting high nitrogen removal requirements, there is a need to implement anammox removal technology. However, the full scale demonstration showed that even if the potential is clearly there, the technology is not yet mature enough to be commonly implemented during cold (<15°C), diluted (low NH_4N concentrations) and unfavourable (high) COD to N conditions in the wastewater, why further full scale demonstrations are highly recommended. Under more favourable, and especially warmer wastewater conditions, the anammox technology is today ready for the early frontrunners.

Finally, the power of an advanced control strategy for conventional nitrification and denitrification should not be underestimated. With an optimised extraction of primary organic carbon, a large increase of biogas and energy recovery can be obtained without jeopardizing the nitrogen limits. This strategy is ready for implementation and should be evaluated on all wastewater treatment plants.

1. Introduction

1.1. The energy positive wastewater treatment plant

Don't underestimate the power of wastewater. This sentence summarises the objective of the EU co-funded project POWERSTEP – a project led by research and industry players working to convert sewage treatment plants into power production facilities while still achieving high quality water treatment. In Europe, the municipal wastewater sector currently consumes the annual power generated by two large power plants. Concurrently, organic matter contained in municipal wastewater accounts for 12 times as much chemical energy potential. In conventional wastewater treatment, the majority of this organic matter, or carbon source, is generally being oxidized in aerobic biological treatment and/or used for nitrogen removal through denitrification. To achieve energy-positive wastewater treatment plants (WWTPs), however, this carbon source should instead be utilized to produce biogas.

An increased carbon extraction for biogas production typically challenges nitrogen removal in conventional wastewater treatment plants, given the dependence of denitrifying bacteria on an easily accessible source of carbon. Thus, POWERSTEP focused on different concepts to overcome this barrier and to guarantee extensive nitrogen removal with a minimum of carbon. Three different concepts have been demonstrated; Advanced control strategies – optimising carbon extraction based on the minimal carbon required for a defined nitrogen removal; Main stream deammonification – where anammox bacteria remove nitrogen without the requirement of organic carbon for nitrogen removal; Main stream duckweed reactor – where photosynthesis production of biomass also provide nutrient removal in stoichiometric favourable conditions. These three strategies represent promising options after advanced carbon extraction with lower carbon requirements for nitrogen removal compared to traditional nitrogen removal.

1.2. Traditional nitrogen removal

Traditional nitrogen removal typically consists of two steps: aerobic oxidation of ammonia to nitrate (i.e. nitrification) and the anoxic conversion of nitrate to nitrogen gas by heterotrophic bacteria (i.e. denitrification). Nitrification is performed in two steps, by two groups of autotrophic bacteria. The first step is the oxidation of ammonia to nitrite performed by a group of ammonium oxidizing bacteria (AOB) (Equation 1). The best known AOB belongs to the genera *Nitrosomonas* (Sliekers et al., 2002). However, *Nitrospira, Nitrosococcus,* and *Nitrosolobus* are also capable to convert ammonia to nitrite (Ahn, 2006).

$$NH_4^+ + \frac{3}{2}O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (1)$$

The second step in nitrification is the conversion of nitrite to nitrate, performed by a group of nitrite oxidizing bacteria (NOB) (Equation 2). The main NOB in biological wastewater treatment belongs to *Nitrobacter* and *Nitrospira* (Sliekers et al., 2002).

$$NO_2^- + \frac{1}{2}O_2 \rightarrow NO_3^- \quad (2)$$

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Denitrification can be performed by many different kinds of heterotrophic bacteria, using nitrate or nitrite as an electron acceptor in the absence of oxygen, and requires the availability of carbon (Equation 3). In wastewater treatment the carbon used for denitrification can either be sourced from the wastewater or added as an external carbon source, typically in the form of methanol, ethanol, acetate or glycerine.

$$2NO_3^- + H^+ + organic\ matter \rightarrow N_2 + HCO_3^- \quad (3)$$

Traditional nitrogen removal with nitrification and denitrification can be applied at the WWTP with a range of different technologies including continuous flow activated sludge systems, sequencing batch reactors (SBRs), fixed film (trickling filters, suspended plastic carriers, aerated filters) and granules. In Case Study 1 Westewitz, traditional nitrogen removal was performed in two SBRs, where the wastewater was treated by activated sludge process with biological phosphorus removal, intermittent nitrification and denitrification (controlled by online measurements of dissolved oxygen) followed by settling and decanting.

1.3. Anammox, nitritation and the MBBR

The deammonification process relies on specialised autotrophic bacteria with anaerobic ammonium oxidation (AnAOB), also called anammox. Ammonium and nitrite are reduced under anoxic conditions without any requirements of organic carbon (Equation 4) and with up to 60% savings of oxygen compared to traditional nitrification-denitrification (Wett et al., 2013).

$$\mathrm{NH_4^+ + 1.32NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow 1.02N_2 + 0.26NO_3^- + 0.26CH_2O_{0.5}N_{0.15} + 2.03H_2O} \quad (4)$$

The reaction for simultaneous performance of AOB and AnAOB is shown in Equation 5.

$$\mathrm{NH_4^+} + 0.804O_2 + 0.071HCO_3^- \rightarrow \mathrm{0.436N_2 + 0.11NO_3^-} + 0.009C_5\mathrm{H}_7\mathrm{O}_2\mathrm{N} + \mathrm{0.028CH_2O_{0.5}N_{0.15}} + \mathrm{0.038H^+ + 1.46H_2O} \quad (5)$$

Since AnAOB use nitrite, it is essential that the deammonification process only contains AOB and AnAOB, and prevents the establishment of NOB. Another key challenge in the deammonification process is the slow growth of anammox bacteria. Hence, the first successful implementations of deamonification for wastewater treatment were done in high-strength sidestream wastewater from dewatering of sludge liquor (i.e. reject water), where high temperature, high ammonia concentrations and low carbon content secure favourable conditions for anammox growth. Today, a wide range of technologies for sidestream treatment with anammox can be found based on both suspended sludge, granules and fixed film, with more than 100 installations completed worldwide by 2014 (Lackner et al., 2014). However, only a minor part of the total nitrogen to be treated is found in the sidestream line, and the great benefit is not obtained until deammonification is applied in the mainstream line with maximised carbon extraction upstream.

Major challenges are still to be overcome for mainstream application of deammonification: (i) low temperature, (ii) low substrate concentration, (iii) high COD/N ratio, (iv) ability to retain anammox in the system, (v) efficient nitrite oxidizing bacteria (NOB) washout and (vi) final effluent quality (Xu et al., 2015). Out of all these challenges, an efficient NOB washout strategy and a robust and easy way to retain anammox in the system are seen as the most challenging ones (De Clippeleir et al., 2013; Gustavsson et al., 2012; Wett et al., 2013).

The Moving Bed Biofilm Reactor (MBBR) process, where bacteria are growing as a biofilm on suspended carriers, offers the high flexibility required to meet these challenges. In the MBBR, slow growing bacteria will safely be retained in the reactor also at low temperatures and at high hydraulic flows, and the MBBR can be staged in series to promote enrichment of different groups of bacteria dependent on reactor conditions and substrate availability. But although the MBBR is ideal for retaining slow growing bacteria, NOB bacteria can still thrive at mainstream conditions, and out-compete the anammox for nitrite. Hence, careful operation strategies are required to ensure stable mainstream deammonification.

1.4. Mainstream deammonification

Deammonification for treatment of reject water in a one-stage MBBR (Christensson et al., 2013) (see Figure 1) is a state of the art technology and full scale processes have been installed worldwide (Lackner et al., 2014). Although one-stage MBBRs have been used to achieve deammonification under mainstream conditions (Gilbert et al., 2014; Gustavsson et al., 2014; Lemaire et al., 2014), the challenges of inhibiting NOB remains. In order to prevent NOB establishment and avoid oxygen inhibition of AnAOB, one-stage deamonification MBBRs must generally operate at low dissolved oxygen (DO) concentrations, which limits the activity of AOB.

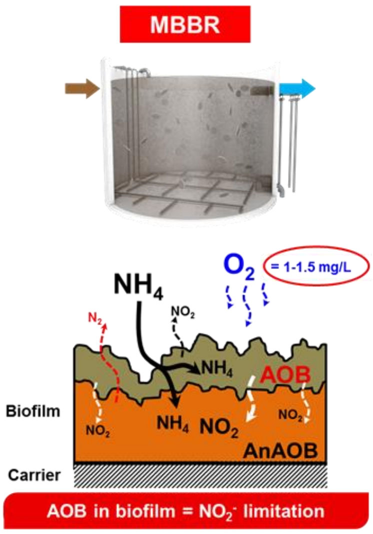

Figure 1: The concept of one-stage deammonification in the MBBR configuration

Since the AOB supplies nitrite to the AnAOB, a limited AOB activity results in limited nitrite availability for AnAOB, which slows down the overall removal rate of the process. In addition, if established in the biofilm, NOB can be difficult to inhibit without damaging the AnAOB population when grown in the same biofilm.

Interesting approaches to avoid NOB establishment in mainstream deammonification are the two-stage MBBR (Piculell et al., 2016a) (Figure 2) and the one-stage Integrated Fixed film Activated Sludge (IFAS) MBBR (Veuillet et al., 2014) (Figure 3) configurations, in which the AOB and AnAOB biomass are grown in separate biomass fractions.

In the first phase of the POWERSTEP project, the novel approach to mainstream deamonification with a two-stage MBBR configuration (Piculell et al., 2016a) was demonstrated in large-scale. In this two-stage configuration, the first reactor was aerated at high DO to achieve efficient nitritation (N-stage), followed by an anoxic, mechanically mixed anammox reactor (AMX-stage) (Figure 2). In order to ensure NOB suppression in the aerated stage, the biofilm thickness was maintained below 200 µm by using an engineered biofilm carrier, specifically developed for biofilm thickness control (Piculell et al., 2016). In addition, the feed to the N-stage was periodically switched from low-strength, low-temperature mainstream wastewater to reject water at high temperatures and concentrations. This sudden exposure to high substrate concentrations and temperatures was expected to inhibit NOB growth in the thin biofilm, and possibly also boost AOB activity (Piculell et al., 2016b). This concept had been shown feasible in achieving stable nitritation at mainstream conditions in both lab- and pilot-scale (Carlsson et al., 2016; Piculell et al., 2016a), but evaluation of full-scale implementation at real wastewater conditions and ambient temperatures remained to be performed.

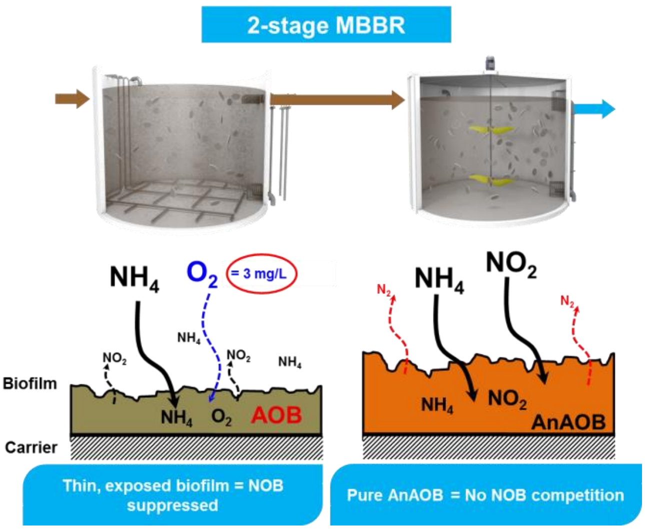

Figure 2: The concept of two-stage deammonification using MBBRs and biofilm control

In the second phase of the POWERSTEP project, a one-stage IFAS MBBR process for mainstream deammonification was evaluated. The IFAS process consists of a regular one-stage MBBR with the addition of an external settler allowing sludge retention (Figure 3). With this configuration, AnAOB preferentially grow in the biofilm while the aerobic AOB (and NOB) tend to grow in the suspended sludge. This robust physical separation between AnAOB-rich biofilm carriers and AOB-rich suspended sludge allows for control of the sludge age in the system and therefore selective wash-out of NOB while retaining anammox. The concept has been studied for mainstream treatment in pilot scale at real wastewater conditions with promising results (Lemaire et al., 2016), but remained to be validated in larger scale.

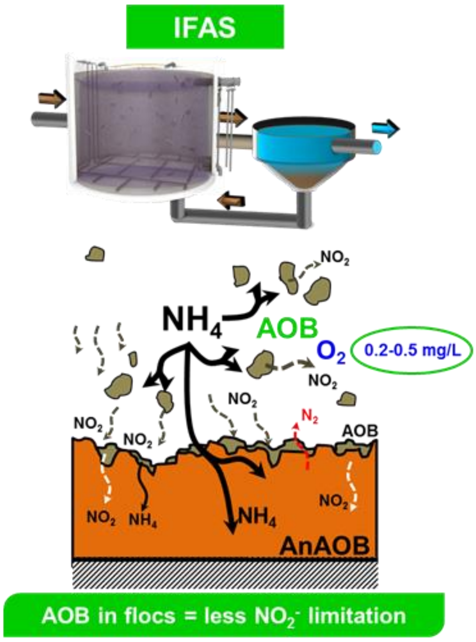

Figure 3: The concept of one-stage deammonification in IFAS MBBR configuration

1.5. Duckweed

Microalgae or duckweed ponds have been used for decades for the treatment of wastewater, especially in warm and sunny regions as polishing step in stabilization ponds or High Rate Algal Ponds (Iqbal, 1999; Shelef, 1984). Duckweeds are the smallest and fastest growing flowering plants found in the plant kingdom (Wang, 2014b). They are aquatic plants floating on or below the surface of still and nutrient-rich fresh and brackish waters forming dense homogeneous or heterogeneous clonal populations (Armstrong, 2011; Skillicorn, 1993). The preference of duckweeds for ammonium over nitrate (NO_3) has been examined in several individual investigations (Fang, 2007; Lüond, 1980; Porath, 1982) and is stated throughout the literature (Hasan, 2009; ORON, 1988; Wang, 2016). Growth rates of duckweed are greatly dependent on temperature with varying optimal requirements for different duckweed species (Landolt, 1987). They grow at water temperatures between 6 and 33 °C (Leng, 1995). In wastewater treatment duckweeds are of interest especially because of their ability to thrive on nutrient rich media and remove nutrients from the water by binding them into their biomass. The biomass composition of duckweeds is of interest for bioenergy production as well as feed and food supplement.

In POWERSTEP, the duckweed concept was studied in three different stages. First batch test were performed in the lab to identify optimal duckweed species, growth conditions and anticipated ammonium removal rates. Secondly, the concept was tested in a continuous pilot plant to give proof of concept with focus on ammonium removal. Finally, the concept was studied in a full scale pilot plant at Westewitz (Figure 4), treating nitrogen rich effluent from carbon extraction with drum filter.

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Figure 4: Full scale duckweed pilot plant (left) with detailed pucture of the trays (middle) and trays with duckweed during operation (right)

2. Carbon extraction

2.1. Overview

Producing more biogas via sludge digestion is the key to achieve energy-neutral or even energy-producing WWTPs, and it goes hand in hand with an efficient primary treatment to remove as much primary sludge as possible from the system (30-80% of total COD) prior to biological treatment. Many technologies, including conventional primary clarifiers, can ensure an efficient withdrawal of the primary sludge, and reduce the needs for aeration in the biological treatment downstream (Figure 5).

Primary settlers based on gravity settling are the most common type of primary treatment, either as standard clarifier or as lamellar settler (e.g. Marquette-Lez-Lille WWTP/FR, 625,000 PE). Typical performances are in the range of 50% suspended solids reduction, corresponding to around 30% of total COD reduction. The same performances can be achieved with microscreens (disc filters and drum filters) on a much more reduced footprint (only 20% of the footprint of conventional settlers), as seen in Agnières-en-Devoluy WWTP/FR (7,000 PE, started up in 2010). Associated to coagulation and flocculation, it has been proved in pilot trials that up to 70-80% removal can be achieved (Remy et al., 2014), i.e. even higher performance than other CEPT (chemically-enhanced primary treatment) or high-load biological stage in a two-stage process (Kirchbichl WWTP/AT, 100,000 PE), that achieve max 50% COD extraction.

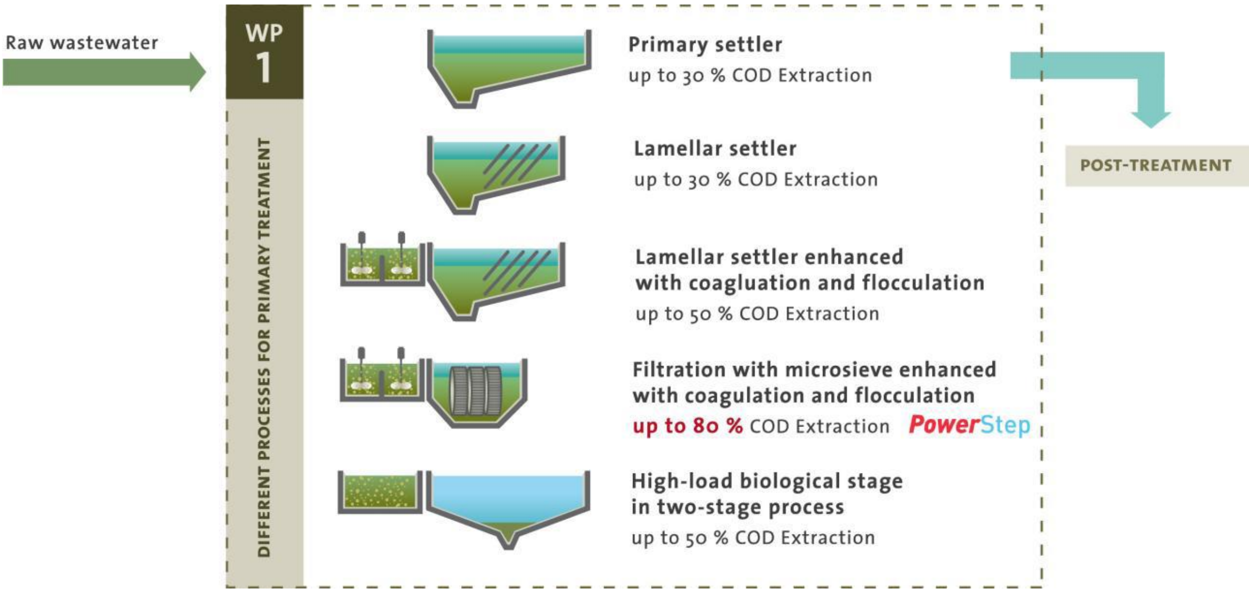

Figure 5: Wastewater treatment process scheme with different primary treatment options

In POWERSTEP, at case study Westewitz, advanced carbon extraction was performed using filtration with microsieve (Hydrotech g filter) with coagulation and flocculation prior to parallel treatment in SBRs and duckweed. At case study Sjölunda WWTP, two different technologies for advanced carbon extraction prior to nitrogen removal with anammox, were applied. In the first phase, enhanced carbon extraction was done with high rate activated sludge (HRAS) process, prior to the mainstream anammox treatment. During this first phase initial trials and optimisation of microsieve filtration, with

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Hydrotech disc filter, was performed in parallel to the HRAS. In the second phase, enhanced carbon extraction prior to mainstream anammox was performed with Hydrotech drum filter only.

3. Operation options after advanced carbon extraction

3.1. Advanced control

Since the biogas potential of primary sludge is higher than the potential of excess sludge, the idea for energy producing wastewater treatments plants (WWTPs) is to extract as much carbon before the biological step as possible in order to produce more biogas on the one hand and reduce the energy needed for aeration on the other hand. But the disadvantage of carbon extraction is that it leads to a change of the influent characteristics, especially the COD/N ratio. This can cause malfunctions of the biological treatment process including deterioration of settleability, of biological phosphorus removal and most important of nitrogen removal.

The solution to prevent any of those potential disadvantages is to find the optimal balance between maximal carbon extraction and process results. With an advanced process control, tested in Case Study 1 (WWTP Westewitz), targeted nitrogen removal can be achieved with minimal COD/N ratios. The following three parts were implemented in

Case Study 1:

1. In standard operation (independent of the nitrate concentration) the remaining carbon must be utilized as efficient as possible with a new feeding regime for the SBRs (providing carbon during denitrification phase, when it is needed) and optimized aeration control. For optimised aeration times are controlled by depletion of dissolved oxygen to avoid loss of COD due to oxidation.
2. Also independent of the nitrate concentration recycling of process water, which is formed while sludge thickening and has high available COD, should be improved by a more regular time based withdrawal regime providing additional carbon.
3. As a backup strategy to prevent high nitrate concentration in the WWTP effluent, the WWTP process control system was equipped with special control mechanisms (see Figure 5) that are automatically activated by increased nitrogen concentrations in the SBRs to supply carbon for denitrification:
    i. Reduction of COD extraction by reduction of chemical dosing
    ii. Bypass of the filtration, meaning direct feeding of the SBRs with carbon rich wastewater
    iii. Nitrate concentration triggered supernatant withdrawal during denitrification times
    iv. Acetate dosing

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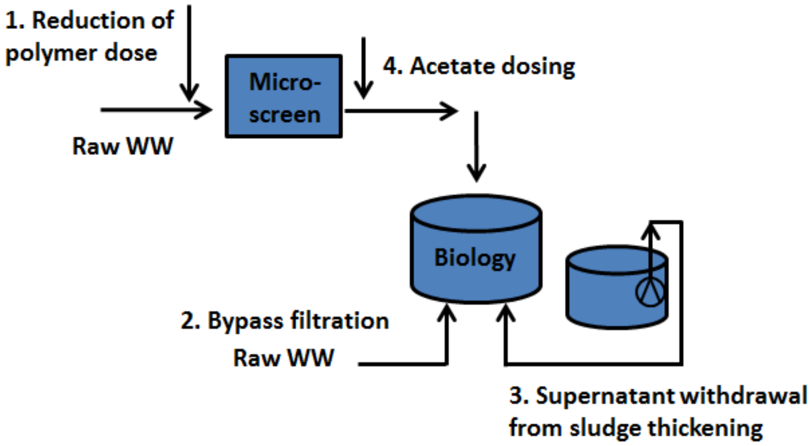

Figure 6: Schematic description of special mechanisms for advanced nitrogen control applied after microscreen

The principle applied in Case Study 1 can generally be applied with other carbon extraction technologies, such as enhanced primary settling and flotation. If a higher carbon extraction is targeted than can be maintained with conventional nitrification and denitrification, alternative N removal technologies should be considered.

3.2. Anammox technology

The full potential of carbon recovery is not reached until a nitrogen removal technology that has no requirements for organic carbon is applied. With the anammox technology this condition is met and in addition with up to 60% savings of oxygen compared to the traditional nitrification. However, even with a main target of extracting maximal amount of carbon, there is a balance between the additional costs for increasing the carbon extracted further (with for instance polymer and/or coagulants) and the increased gained energy generated from that. In addition, there can be both advantages and disadvantages, with any remaining COD entering the subsequent nitrogen removal stage. For instance in Case Study 2 Sjölunda WWTP, the high rate activated sludge (HRAS) reactor used in the first phase gave a different wastewater characteristics after carbon extraction compared to the wastewater obtained when a microsieve with drum filter was used and this gave a significant effect on the subsequent nitrogen removal.

3.3. Duckweed

Another alternative, where the full potential of carbon recovery can be reached is to use microalgae or duckweed ponds for the treatment. Duckweed can be found in various habitats all over the world due to their wide range of tolerable living conditions. They mainly grow in shallow waterbodies, converting the nutrients and minerals into biomass. Under optimal growth conditions the fastest of the duckweed species can double its biomass within 29.8 hours, which corresponds with a relative growth rate of 0.56 d-1 (Sree, Sudakaran et al., 2015).

3.4. Other options

To the best of our knowledge, there are no other biological options to anammox and microalgae/duckweed after complete carbon extraction when nitrogen is to be removed in wastewater. Even extremely low loaded systems relying on simultaneous nitrification and denitrification require some carbon supply. The only true option is then to use non-biological nitrogen removal technologies, such as ammonia distillation/stripping, ion-exchange, precipitation (eg. struvite) and/or membranes (reverse osmosis). These technologies have to a certain degree been successful in removing nitrogen from concentrated streams, such as the sidestream from sludge dewatering.

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4. Guideline for process choice after advanced carbon extraction

Each process option, based on biological or physical treatment of nitrogen, after advanced carbon extraction has its pros and cons. A guideline, primary based on the outcome from deliverables within the POWERSTEP project, but also in comparison with other technology not included in POWERSTEP, is given in table 1. The comparison is relative to conventional nitrogen removal using activated sludge, without giving any absolute numbers and is far from complete and with the only purpose to highlight some of the pros and cons, based on the outcome and knowledge gained from POWERSTEP, when choosing a suitable process option after advanced carbon extraction.

Table 1: Key characteristics for different options of nitrogen removal after advanced carbon extraction in comparison to common conventional nitrogen removal with activated sludge

Options	Energy requirement	Foot print	Chemical consumption	Removal performance	Stability	Sludge production	Readiness for sidestream	Readiness for mainstream
Advanced control	Low/ Medium	Medium	High	High	High	Medium	n.a.	High
Anammox	Low	Medium	Low/ Medium	Medium	Medium	Low	High	Low/ Medium
Duckweed	Low/ Medium	High	Low/ Medium	Low/ Medium	Low	Medium	n.a.	Low
Reverse osmosis	High	Low	Medium	High	High	n.a.	Low	Low
Ion exchange	Medium	Low	Medium	Medium/ High	Medium/ High	n.a.	Low	Low
Struvite precipitation	Medium	Low	High	Medium/ High	Medium/ High	n.a.	High	Low
Ammonia stripping	Medium	Low	High	Medium/ High	Medium/ High	n.a.	HIgh	Low

n.a. = not applicable

4.1. Advanced control

Advanced control of the carbon extraction makes it possible to optimise the carbon recovery and still meet the discharge requirement for nitrogen. The increased energy gained through optimised carbon extraction makes the overall *energy requirement* lower, especially if the aeration demand is well controlled. However, even in an optimised process, the carbon and air demand is still there. The *footprint* for the pre-treatment can dramatically be reduced when a microsieve (such as the Hydrotech drum filter) is used for carbon extraction. The footprint for the biology is also reduced due to more efficient removal and operation. *Chemical consumption* can be high for polymer and coagulants and the costs for that should be balanced towards the gain of energy through increased carbon extraction. The *removal performance* can be high if required, but higher nitrogen removal performance means less carbon extracted. The *stability* of the process is high and the targeted nitrogen concentration can be met with a well calibrated control system. Since a higher fraction of the carbon goes to anaerobic biogas treatment, the *sludge production* in the overall system decrease slightly, but is still significant. Enhanced carbon extraction in *sidestream treatment* is not applicable due to the low carbon content in sidestream water. The advanced control system for enhanced carbon extraction is ready to be applied in most *mainstream treatment* systems with nitrogen removal requirements.

4.2. Anammox removal

With an **anammox removal** technology, such as the ANITA™ Mox process used in task 2.2 at Case Study 2 Sjölunda WWTP, a maximized carbon extraction can be applied and still achieving a high nitrogen removal efficiency. The *energy requirement* for the process is low since less (≈ 60%) oxygen is required and there is no need for organic carbon for the nitrogen removal. Footprint can potentially be low in a pure ANITA™ Mox MBBR system, where both nitritation and anammox takes place in a biofilm system. In an IFAS ANITA™ Mox MBBR, where nitritation takes place in the suspended activated sludge flocs, the demand for critical SRT and settler for the sludge, makes the overall foot print still significant, even if the overall *footprint* is lower compared to a conventional activated sludge, which requires an even higher SRT than the IFAS anammox process. The *chemical consumption* depends on the applied carbon extraction method. If a high rate activated sludge system is used, as in phase 1 in Case Study 2 Sjölunda WWTP, the chemical consumption is low, whereas if enhanced precipitation is used, as in phase 2, the chemical consumption is significant. The *removal performance* with an anammox technology can be good, but typically not exceptional. It is possible to reach < 10 mg N/l, but for lower discharge levels post-treatment may be required. The *stability* of the anammox technology is dependent on good control of wastewater characteristics, aeration and SRT control.

For favourable conditions, such as high temperature and low COD/N ratio, the anammox technology has proven stable and robust, but opposite, at low temperature (<15°C) and diluted (low NH_4N concentrations) wastewater with a rather high COD/N ratio, the stability has been lost. In Case Study 2 Sjölunda WWTP, the concept of mainstream anammox technology was proven, but the stability was not obtained for the challenging wastewater characteristics and the suppression of NOB could not be established on a long-term base. The *sludge production* with anammox bacteria is low and since no requirement of carbon source is required for nitrogen removal, the overall sludge production is very low. Even if the anammox technology is now a mature and established technology for *sidestream treatment*, with more than 100 full-scale installations completed worldwide by 2014 (Lackner et al., 2014), the readiness for *mainstream* applications is rather low for the colder conditions typically found in northern Europe. However, with only a couple of degrees increase in the wastewater, the conditions are there for successful implementation.

4.3. Duckweed

The duckweed technology has no requirement for aeration and makes use of day light for growth, giving an overall *low energy requirement*. For 24/7 treatment, artificial light requirement using efficient LED lamps is applied, which increase the overall energy requirement. Due to the shallow water depth (<10cm) and long hydraulic retention time (≈ 24 hours), the *foot print* is high, even when treatment is performed in parallel treatment lines stacked on top of each other with artificial light supply. No *chemical supply* is required for the duckweed growth, but enhanced carbon extraction with for instance microsieves requires polymer and/or coagulants. *Removal performance* is very temperature dependent and in summer time (19-26°C) in Case Study 1 Westewitz a 60-100% NH4N removal efficiency and 40-70% TN removal efficiency was obtained, whereas in winter time (8-17°C) the NH4N removal was down to 37-50% and the TN removal to 17 -40%. The *stability* of the process is challenged by growth of other duckweed species or algae with lower ammonia and nitrogen removal efficiency and to maintain an optimal mat density for optimal growth rate. The duckweed production is low since doubling time is long (1-10 days). In spite of promising results in Case Study 1 Westewitz WWTP, the readiness for the main treatment process using duckweed is still low, and more development and demonstration is required.

4.4. Other options

Of the non-biological nitrogen removal options mentioned in table 1, struvite precipitation and ammonia membrane stripping/ ammonia air stripping are the ones that have been applied for nitrogen removal in sidestream treatment. Struvite precipitation requires addition of magnesium and a high presence of phosphate in order to be a viable solution. In both ammonia membrane stripping and ammonia air stripping, there is a significant chemical requirement for pH changes. An extensive pre-treatment is typically required before the membrane unit, including storage tank, CO_2-stripper, Coagulation+flocculation with lamella sedimentation, sandfiltration with subsequent cartridge filter and heat exchanger. The NH_4N elimination is then around 80% and N-removal around 70%. An important advantage is the recovery of nitrogen into a valuable product. When it comes to mainstream application, all mentioned non-biological technologies are far from readiness to be implemented. However, if (or when) this takes place a possible approach could be to recover the ammonium (and phosphate) in the effluent from the biological stage, where soluble COD and total suspended solids are low using either reverse osmosis, ion-exchange, struvite precipitation or ammonia membrane stripping.

5. Final remarks

Enhanced carbon extraction provides a unique possibility to dramatically improve the overall energy efficiency at the municipal treatment plant, but it also challenges the traditional ways to maintain a high nitrogen removal treatment. In POWERSTEP several tools that address both improved energy yield and alternative ways for nitrogen removal treatment have been demonstrated. In work package 2, three different nitrogen removal strategies have been demonstrated in full-scale; Advanced control, Anammox technology with ANITA™ Mox and Duckweed technology. Based on the outcome from these demonstration projects, as well as on general knowledge on some alternative nitrogen removal strategies, the best available options for nitrogen removal after advanced carbon extraction has been evaluated. It can be concluded that the implementation of advanced control should always be evaluated, since this proved to work well in Case Study 1 Westewitz WWTP and it is built upon established technology and microbial pathways. However, the full potential of energy recovery can only be met when nitrogen is removed with a technology without any requirements for organic carbon. The non-biological methods are today far from readiness and the only true candidate seems to be based on the anammox technology. The results from Case Study 2 Sjölunda WWTP where anammox with ANITA™ Mox was demonstrated, proved the concept to be viable, but also showed the challenges that occur at low temperature and diluted wastewater with high COD to N ratio. With higher temperature and more favourable wastewater conditions, the IFAS ANITA™ Mox technology has proved to give a high stability and efficient nitrogen removal efficiency, ready for commercialization.

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