Environment Agency

What are the different types of sewage treatment processes commonly used for nitrogen reduction?

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Primary Question

We would like to establish the different types of sewage treatment processes commonly used in the UK, or other European Countries with a similar climate, in terms of nitrogen (N) reduction at sewage/wastewater treatment works. This should include typical secondary treatment methods (not designed to specifically reduce N) and also tertiary treatment methods which aim to reduce N.

Background

The Urban Waste Water Treatment Directive (UWWTD) uniform emission limit values (UELVs) for N (10-15 mg/l) in sewage treatment works (STWs) effluents provided an initial benchmark for technically acceptable limits of nutrient reduction in the early 1990s. From the late 1990s when UWWTR nutrient reduction requirements in Sensitive Areas (Eutrophic) began to be applied in England, they were initially based predominantly on the UWWTR UELVs. This was alongside requirements in Sensitive Area (Nitrate) where no specific nitrogen limits were set.

In more recent times, a need for bespoke effluent limits, often more stringent than the UWWTR values, has been driven by the nutrient standards for good ecological status or targets for favourable condition, set for Water Framework Directive (WFD) and Habitats Directive purposes. The role of N in freshwater eutrophication, particularly lakes and reservoirs, has become increasingly recognised as being important in recent years and UK Technical Advisory Group on the WFD (UKTAG) has now developed N standards for standing fresh waters. It is anticipated that these will be applied in River Basin Management Plans (RBMPs) 3rd Cycle and are likely to drive N reduction in 2024 Price Review (PR24) and beyond at STWs affecting failing eutrophic water bodies.

This literature review will inform Environment Agency work into establishing what is technically achievable for water companies in terms of nitrogen concentrations in treated sewage effluent.

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The scope of the literature search covers the UK and Europe and other countries with a similar climate within a date range of the last ten years.

Results Summary

- As well as legislative requirements, innovation in N removal processes highlight the need to minimise energy and organic carbon consumption as part of a wider societal and environmental shift towards sustainable development and water resource recovery
- Advances in molecular microbial probing have allowed for analyses of the microbial community of WWTPs; knowing microbial community structure can reveal correlations with environmental and operational parameters
- There is extensive research around the development of the autotrophic anaerobic ammonia oxidation (anammox) process, which has already found widespread application in the treatment of high-strength wastewater

Results

A list of the references with standard bibliographic information, annotations and links to full text articles and grey literature resources can be found in the Knowledge Map, Nitrogen Reduction_KnowledgeMap.xlsx, to accompany this document. Where information was available the following details have been transcribed: Study Type, Treatment, Influent Concentration, Effluent Concentration and the Reduction Efficiency, to express the denitrification rate.

The bibliometric information from the Knowledge Map indicates that the majority of research into techniques for nitrogen reduction have been published in China. Overall, most of the study types have been conducted at laboratory scale, and based on the research methods have tested a heterogenous mix of treatment types. There is a broad range of influent concentrations but most treatment technologies achieved results below 10 mg/l through high percentage reductions at the peak stage of the denitrification process.

According to a global survey of the most advanced processes for wastewater nitrogen removal, reported in Capodaglio et al., (2016), biological processes are widely applied to the treatment of both municipal and industrial wastewater. Whereas physical-chemical processes tend to be associated with highly concentrated wastewater such as landfill leachate, which require both a high temperature and pH (see earlier review by Capodaglio et al., 2015).

Biological processes are based on the action of heterotrophic bacteria that, under anoxic conditions, carry out the biochemical reduction of nitrate to nitrogen gas. At present, the dominant technology is pre-denitrification in activated sludge systems.

Research in this field is mainly focused on evaluating optimal sizing criteria for the denitrification reactor. One of the key performance factors is represented by dissolved oxygen (DO) inhibition on the denitrification rate; thus, technological improvements that can reduce DO presence in the anoxic stage are among the most relevant (Capodaglio et al., 2016).

As well as the goal of reducing nitrogen in effluent to prevent aquatic eutrophication and the aforementioned European legislation, research by Li et al., (2016) and Merlo et al., (2012) draw attention to more stringent criteria formulated at national level in China and the U.S. in the range of <10 - 1mg/l, particularly with regards to areas of sensitive aquatic ecology. In response to the burgeoning requirements of extended nitrogen removal, many existing municipal wastewater treatment plants (WWTPs) at a global level are facing the need of upgrading tertiary units.

Other drivers of innovation highlight the need to minimise energy and organic carbon consumption by nitrogen removal processes as part of a wider societal and environmental shift towards sustainable development and water resource recovery (Li et al., 2020). However, according to Hauck et al., (2015) there is also a growing body of research focussing on the trade-off between greater nitrogen removal efficiencies and energy and chemical demands, and greenhouse gas emissions and operational costs, when comparing different types of wastewater treatment.

These trade-offs are explored both by Li et al., (2016) and Jiang et al. (2020), finding that among the variety of potential treatment options for nitrogen, biological heterotrophic denitrification via an additional, external carbon source has traditionally proved to be an effective method. The most preferred carbon additives have been liquid sources such as methanol, ethanol, acetic acid, or glucose.

Nitrogenous pollution in the effluent of traditional biological nitrogen removal processes is mainly in the form of nitrate, due to a limited biodegradable carbon source for denitrification. To date, a post-denitrification biofilter is the most widely used practical technology for tertiary nitrogen removal in WWTPs. External carbon sources, such as methanol, ethanol, acetate and glucose, are added after the biofilter to remove excess nitrate.

Although aerobic activated sludge processes are efficient in removing organic material and nutrients, with the potential to achieve a TN level of 1mg/l, the aerobic process is encountering more critiques as it requires a large amount of energy (mainly for aeration). They also produce large amounts of excess sludge and additional performance is contingent on an external carbon source for denitrification (Hendrickx et al., 2012).

Furthermore, the cost of adding liquid carbon sources is typically high. The control and management of liquid carbon sources present major problems, for example, some flammable carbon sources, such as methanol and ethanol, give rise to security hazards for transportation, storage and operation. Moreover, a considerable portion of liquid carbon sources is inefficiently utilised by non-denitrifying bacteria, resulting in a large amount of excess sludge (Che et al., 2017 and Li et al., 2020).

Another operational challenge for conventional post-denitrification biofilters is the accurate control of external carbon addition. Whilst nitrate and nitrite can breach effluent limits as a result of insufficient carbon dosage, an overdose of the carbon source increases the chemical oxygen demand (COD) concentration in the effluent, creating a new pollutant. Hence, many researchers are committed to developing a technology that will be stable in performance, safe to operate and simple to control (ibid.).

According to Li et al., (2020) the performance activated sludge systems are frequently influenced by additional factors such as low chemical oxygen demand/nitrogen (COD/N) ratio, temperature, sludge bulking, biomass and influent load fluctuation. In particular, a low COD/N ratio aggravates the difficulty of achieving satisfactory performance because it lacks a sufficient carbon source for heterotrophic denitrification.

Though they are the most commonly employed biological process activated sludge systems are highly complex where a wide variety of bacteria play dominant roles in pollutant degradation and removal. It has long been accepted that the diversity of functional bacteria closely correlates with the removal efficiency of pollutants, it also influences the stability and sustainability of WWTPs. So, elucidating the influencing factors behind the biodiversity of nitrogen-cycle bacteria is particularly important to optimise the condition for nitrogen removal (Che et al., 2017).

According to Wiggington et al., (2020) knowledge of microbial community composition and diversity in various municipal and industrial WWTPs has been advanced, mainly because of the aid of culture-independent high-throughput sequencing (HTS) techniques. These techniques have provided a description of the microbiome of WWTPs which can identify low abundance and transient taxa in WWTPs communities more accurately than culture-dependent techniques.

Additionally, studies have been carried out to identify the main environmental and operational factors influencing the microbial community composition. Analyses of the microbial community of WWTPs which have shown that communities vary as a function of geography, time, influent type, and zone within a treatment facility. This is based on the expectation that environmental selection - in this case alternating oxic and hypoxic/anoxic conditions - drives microbial community structure. The validity of this assumption can have consequences for effective management.

A study by Che et al. (2017), used a full scale system as the basis for a model of a microbial ecology study. They observed that different transcription levels of functional genes related to nitrogen metabolic pathway have been observed in the samples. Furthermore, elucidating correlations of transcription level with environmental and operational parameters could improve understanding of the conditions that favour the expression of functional genes.

During sludge processing, ammonia is oxidised to nitrite by ammonia monooxygenase enzyme of ammonia oxidising bacteria (AOB), which is believed to be the key step in nitrification process. Therefore, the amoA gene, which has been widely used as biomarker to investigate the AOB in different environments (Wiggington et al., 2020).

A study by Li et al., (2020) sought to understand the bio-toxicity of titanium dioxide nanoparticles (TiO2-NPs) for the performance of biological wastewater treatment systems. Due to their extensive applications in consumer products, these nanoparticles are eventually discharged into sewage systems into WWTPs where they have been detected in in raw sewage, effluents and in the aeration tank in sewage sludge.

The aim of their study was to understand the potential relationship between the microbial community and physicochemical characteristics, and to determine the active ammonia-oxidising microorganisms and nitrogen-removing biofilters in sludge flocs and the internal mechanisms of their responses to TiO2-NPs.

Their main conclusions were that TiO2-NPs exerted strong inhibition on N-cycling, and a modification of the microbial community structure and functional diversity in activated sludge, even at low realistic concentrations (1 mg/L). Also that long-term exposure to TiO2-NPs caused apoptotic-like and necrotic-like cell deaths, which reduced the abundance of ammonia-oxidising archaea and AOB (ibid.).

Research by Wiggington et al., (2020) analysed the metagenomic aspects of both centralised and on-site WWTP performance, to further understand their underlying engineering principles. They reported major differences in ammonia-oxidising and nitrous oxide-reducing community composition and structure between centralised and decentralised biological nutrient removal wastewater treatment systems.

The research also found that indices of community richness and diversity were overall higher in the centralised than in the onsite WWTP. Their analysis suggests that the larger scale of treatment supports a wider variety of denitrifiers. Their findings have implications for resilience to environmental changes such as shifts in climate and influent properties as well as for optimising their operation and maintenance.

There are several additional papers highlighted throughout the Knowledge Map where the N-transforming communities of WWTPs, including ammonia-oxidisers, anammox, comammox, and denitrification have been described. Physical and chemical water properties, including levels of dissolved oxygen and of $NO3^{-}$ and $NH4^{+}$, pH, organic carbon concentration, and temperature, have been identified as important factors shaping the microbial communities responsible for N removal. The research trend of targeting the diversity of functional bacteria associated with nitrogen removal in activated sludge, suggests a rapidly increasing understanding of bacterial community structure, which could influence the future performance of WWTPs (Wiggington et al., 2020).

Amongst the interventions aimed at resolving the performance and sustainability issues associated with conventional urban drainage and wastewater treatment system Hendrickx et al., (2012), decentralised treatment of separated household waste waters would allow efficient energy recovery through anaerobic treatment of the concentrated (and warmer) black water. This would require a new infrastructure for waste water collection and is, therefore, mainly interesting for new-built residential areas.

Yao et al. (2017), have suggested that source separation and treatment of human urine have been recognised as a resource-efficient alternative to conventional urban drainage and wastewater treatment system, as urine accounts for 80% of nitrogen (N) and 50% of phosphorus (P) loads on domestic wastewater. Due to the higher concentrations of P and N in urine than domestic wastewater, efficient recovery and/or removal of these nutrients from urine could be more cost-effectively achieved.

Their study proposes a process for nutrient recovery/removal from urine can be implemented at household and building level provided that process operation could be properly maintained. The effluent can be discharged to sewer drainage, thus the influences on both the wastewater composition and the nutrient loads on municipal waste treatment plant would be greatly minimised.

Amongst the tertiary treatment interventions within the Knowledge Map, research by Liang et al., (2018) proposed an energy self-sufficient sewage treatment plant utilising organic matter to produce anaerobic biogas. As well as phosphorus recovery the "completely autotrophic nitrogen removal over nitrite" (CANON) process for treating low-ammonia domestic sewage at room temperature. The research suggests that autotrophic nitrogen removal process could save aeration and organic carbon consumption when compared with conventional nitrification-denitrification process.

With regards to the denitrification efficiency in small treatment plants Capodaglio et al. (2016) report that large variations in quantity and quality of sewage, typical of small communities, make it hard to achieve high biological denitrification efficiencies (i.e. N ≥ 90%). However, by adding supplemental carbon, it has been possible to overcome the difficulties encountered and achieve denitrification efficiencies greater than 90%.

According to Zhang et al. (2019) solid-phase denitrification has been recognised as an attractive emerging alternative, in which the carbon source for biological denitrification is accessible from microbial decomposition of organic solid. Compared to conventional post-denitrification biofilter, solid-phase denitrification is a simple process; that does not require a sophisticated and costly process control system and avoids the risk of under- and overdosing of the soluble carbon source

In the last decade, several types of biodegradable polyesters, including polylactic acid (PLA), polycaprolactone (PCL), polyhydroxybutyrate-hydroxyvalerate (PHBV), poly butylene succinate (PBS), have been tested for use as solid carbon sources for denitrification.

Compared to other solid carbon source such as PHB, the advantage of PCL is high efficiency in denitrification. While compared to conventional soluble carbon source such as methanol and sodium acetate, solid-phase denitrification using PCL could achieve very a low risk of excess organic residue and nitrite in effluent. They conclude that if the price of PCL could be reduced to a certain degree, then an integrated solid-phase denitrification biofilter using PCL would become a competitive technology for tertiary denitrification in commerce (ibid.).

A study by Cao et al., (2020), investigated the feasibility of using primary sludge as a solid carbon for denitrification. They argue that the target nitrogen removal performance can be obtained under the appropriate primary sludge dosage. This provides a more easily-operated method to utilise the organics carbon from wasted sludge, a sustainable wastewater treatment can be expected with great economic benefits.

Finally, amongst the key papers highlighted, a long term study by Merlo et al. (2012) examined full-scale organic nitrogen removal by reverse osmosis. The reverse osmosis process was identified as a potential means to reduce effluent total nitrogen to meet more stringent effluent criteria (N <1 mg/l).

The results showed variability in organic N removal. The authors suggest that organic nitrogen characteristics as well as membrane characteristics or process operation can affect its removal (as a function of wastewater characteristics and secondary processes). Furthermore, analytical methods may not be precise enough to measure organic nitrogen. This could mean that organic nitrogen removal is not as variable as it appears and that without testing it is not possible to know the actual organic nitrogen concentration (ibid.).

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Notes

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