

Sara Zajac

Use of hydrocyclones for optimizing  
crucial sludge parameters in CAS  
WWTP,  
focusing on: SVI and required aerobic  
sludge age for maintained nitrification

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## ABSTRACT

In order to address the growing capacity issues that are being brought on by urbanization, this thesis focuses on the potential of hydrocyclone technology to optimize sludge treatment parameters at the Søholt Wastewater Treatment Plant in Silkeborg, Denmark. The amelioration is prioritized in three crucial process indicators: the aerobic sludge age needed to sustain stable nitrification in a traditional activated sludge system, nitrification rates, and the Sludge Volume Index.

Following the installation of a hydrocyclone station in June 2024, the technology's effectiveness was assessed through both primary experimentation and secondary operational data extracted from the plant's Supervisory Control and Data Acquisition system. The controlled aeration of diluted sludge samples with added ammonium chloride was used to evaluate the nitrification performance, while experimental procedures were carried out in compliance with DS/EN 14702-1:2006 for SVI analysis. Additionally, to evaluate the process changes seen after installation, historical data on sludge age and other operational parameters were compared with current values.

Although valuable insights have been found about the role of hydrocyclones in amelioration of sludge settleability and supporting stable nitrification, several limitations have been acknowledged. The limited time frame since installation may not have allowed for the observation of long-term effects, and outcomes may have been influenced by factors such as suboptimal ammonium dosing during nitrification testing, seasonal variations, and changes in influent characteristics over time. Furthermore, variations in historical sludge age data must be interpreted with caution due to potential differences in external conditions.

Despite these limitations, hydrocyclones are presented as a promising tool for enhancing the resilience and efficiency of wastewater treatment processes. The importance of continued monitoring and long-term research is emphasized in order to validate and expand upon these initial findings.

**Keywords:** hydrocyclones, nitrification, sludge, wastewater, sludge age,

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## 1 INTRODUCTION

Wastewater treatment seen over the many centuries has evolved significantly. Dating back to ancient times when civilizations, such as the Romans, used simple filtration methods to manage sewage. And as we know, clean water is vital for public health, as untreated wastewater can be full of pathogens and pollutants that pose serious risks to people and ecosystems. Therefore, it is important for wastewater treatment to evolve. As seen throughout the history, like during the industrial revolution which started the development of more structured systems, leading to the establishment of the first municipal wastewater treatment plants (WWTPs) in the 19th century. (Winther 1998).

Over decades, technologies such as activated sludge processes, membrane bioreactors and hydrocyclones appeared improving the efficiency of the treatment and the reclamation of water for various uses. Today, innovative approaches are on the rise, addressing the growing challenges of urbanization and water scarcity, that pose issues such as significant challenges in capacity leading to operational overload. As more people move to the urban areas, the cities expand, and with them the volume of wastewater generated which often exceeds the designed capacity of these facilities, resulting in inefficiencies and potential environmental hazards. (Mritunjay 2021)

Overloaded plants such as Søholt in Silkeborg, Denmark, may struggle to adequately treat sewage, which can lead to untreated or partially treated wastewater being released into surrounding water bodies, in this case it's the Gudenå which is the longest river in Denmark, which can be posing serious risks to public health and ecosystems. To address these pressing issues, there is an urgent need for investments in infrastructure upgrades, technology enhancements, and the implementation of innovative treatment methods. Søholt is currently at a beginning of larger scale changes, the hydrocyclones are meant to take the load off before the real renovation take place. (Henze 1992)

By increasing the capacity and improving treatment processes, we can ensure that wastewater management systems are resilient and capable of meeting future

demands while safeguarding both human health and the environment. In order to achieve both increased capacity and ameliorated wastewater treatment, Søholt decided to install a hydrocyclone station with five cyclones. Hydrocyclones (HC) were developed in the early 20<sup>th</sup> century due to the need for separation processes in various industries. In the 1940s, they were mostly used in the mining industry and in the 1970s they began being used in wastewater treatment. They operate on the principle of centrifugal force to separate the denser particles (the good ones), and the lighter particles (the bad ones). The denser particles contain the granules and bacteria that is needed back in the process of the WWTP, the lighter particles are often filaments which are thread-like microorganisms that cause issues such as foaming, settling issues which causes the need for increased maintenance and effectiveness of the treatment process due to inhibition of removal of nutrients. (Suez 2022)

**This thesis will focus on the use of hydrocyclones for optimizing crucial sludge parameters in conventional activated sludge (CAS) wastewater treatment plant (WWTP) focusing on sludge volume index (SVI) and required aerobic sludge age for maintained nitrification.**

## **2 THEORY**

Wastewater treatment has been practiced for many decades, centuries even, although the widespread implementation of closed sewer systems only began around the 1800s. Early adopters like London and Paris initially discharged wastewater directly into rivers such as the Thames, leading to severe environmental and public health issues, including foul odours, oxygen depletion, and sludge accumulation, underscoring the need for more advanced wastewater management strategies (Winther 1998). The recognition of the relationship between wastewater treatment, public health, and environmental protection became more prominent in the 1970s. Nevertheless, untreated wastewater was still being discharged into natural water bodies in parts of Europe as late as the early 2000s. This led to ecological degradation due to excessive nutrient loads, which encouraged the introduction of the Urban Wastewater Treatment Directive in 1991 updated in 2024 to further address these concerns (EEA 2022).

Wastewater is generally categorized into domestic, industrial, and stormwater types. The Søholt Wastewater Treatment Plant (WWTP) in Silkeborg, Denmark, where this study is conducted, primarily treats domestic wastewater. The treatment process is structured in stages: primary (mechanical removal of solids via screening, sedimentation, and flotation), secondary (biological treatment through activated sludge, nitrification, and denitrification), and tertiary (chemical disinfection and filtration). In some cases, a quaternary stage may be applied for even higher purification standards (Winther 1998).

Modern challenges in wastewater treatment are multifaceted. Urbanization in towns like Silkeborg is contributing to capacity stress on WWTPs, while climate-related targets demand reductions in greenhouse gas emissions from treatment processes (Hosomi 2016). Additionally, the detection and management of emerging contaminants which are substances that not traditionally monitored but are now recognized as potential risks to human and environmental health, pose new challenges (Kumar 2022). Moreover, wastewater flow is highly variable across time scales, making it essential that WWTPs are designed and operated with flexibility to accommodate both current and future conditions. Taking Søholts location into consideration makes it vulnerable, as it is set low compared to all groundwater, which further increases risks for reduced capacity. (Henze, 1992). This thesis investigates the application of hydrocyclone technology to optimize sludge parameters in a conventional activated sludge (CAS) system. The focus lies specifically on improving the Sludge Volume Index (SVI) and reducing the aerobic sludge age required for effective nitrification, both critical indicators of biological process stability and efficiency. At Søholt WWTP, which serves a population equivalent (PE) of up to 100,000 and discharges into the sensitive Gudenå River, enhancing these parameters is particularly important to safeguard local ecosystems (Roche 2022).

Hydrocyclones are devices that use centrifugal force to separate solids from liquids and were introduced to Søholt in collaboration with SUEZ in April 2024 and became operational by June. This study evaluates the potential of this technology to improve sludge settleability and reduce biological process loading,

thereby supporting enhanced nitrogen removal and more resilient wastewater treatment performance. (SUEZ)

## **2.1 Conventional activated sludge wastewater treatment plant – CAS WWTP**

As mentioned above WWTPs play a crucial role in ensuring that wastewater is treated effectively before being discharged into the environment. These plants are designed to remove contaminants from wastewater to meet environmental and public health standards. The process of wastewater treatment typically involves several stages, each aimed at removing physical, chemical, and biological pollutants. The treatment process begins with preliminary treatment, where large debris, plastics, and solid waste are removed through screens and grit chambers. This step ensures that larger contaminants do not clog the plant's equipment, enabling the next treatment stages to function more efficiently. (Russell 2019)

Once the larger contaminants are removed, usually the wastewater enters the primary treatment stage, which involves settling tanks known as primary clarifiers, there are none of those at Søholt, however. Here, suspended solids are allowed to settle as sludge, removing approximately 60-70% of the solids. While primary treatment effectively removes large particles, it leaves behind dissolved organic matter and some nutrients. The next phase, secondary treatment, is the core of most wastewater treatment plants. This stage relies on biological processes to degrade the remaining organic material. (Innerebne 2017), Microorganisms such as bacteria are introduced into aeration tanks, where they feed on the organic pollutants. According to Chen et al. this process, known as activated sludge, breaks down the organic material into simpler compounds like carbon dioxide and water. Microorganisms play a crucial role in purifying the water, and biological treatment is one of the most widely used methods in both municipal and industrial wastewater treatment. In addition to activated sludge, some wastewater treatment plants employ alternative or complementary systems like biofilm processes or membrane bioreactors. These methods enable microorganisms to form a biofilm on the surface, which enhances the degradation of organic

contaminants. Once the biological treatment is complete, wastewater moves to secondary clarifiers, where the remaining microbial biomass settles out as sludge. The water treated is then ready for tertiary treatment, which involves additional processes to further purify the effluent. Tertiary treatment may include advanced filtration, nutrient removal, and disinfection, often using methods like ultraviolet light or chlorine to ensure that the treated water meets environmental standards before being released or reused. The sludge from the bottom of clarifiers also continues its way towards other processes. At Søholt most returns to as return activated sludge into the inlet of the hydrocyclones and the rest heads towards a digester and dehydrator. The sludge that is not used in hydrocyclones creates two byproducts, methane gas and fertilizer. (Russell 2019)

Nutrient removal is an essential component of wastewater treatment, as excess nutrients like nitrogen and phosphorus can lead to harmful environmental effects such as eutrophication in water bodies as well as harmful algal blooms. Which is an important aspect to keep in mind considering that Gudenå is in a very fragile state. Nitrogen removal typically involves a two-stage biological process. The first stage, nitrification, occurs in the presence of oxygen and involves the oxidation of ammonia to nitrites and then to nitrates. The second stage, denitrification, occurs in anoxic conditions, where specialized bacteria convert nitrates to nitrogen gas, which is released into the atmosphere. This process is crucial for controlling nitrogen levels in treated water and preventing the eutrophication of receiving water bodies. (Theobald et al. 2020)

Phosphorus removal is also a vital aspect of wastewater treatment. Methods such as chemical precipitation or biological uptake by microorganisms are commonly used to remove phosphorus. At Søholt sodium aluminate ( $\text{NaAlO}_2$ ) is used along with ferrous sulphate ( $\text{FeSO}_4$ ). In many plants, an enhanced biological phosphorus removal process is employed (a bio-P tank in case of Søholt which is described in detail in section about hydrocyclones). In this process, specific bacteria take up and store phosphorus under anoxic conditions and release it when exposed to oxygen, facilitating its removal. By using these

advanced techniques, treatment plants are able to reduce nutrient concentrations in effluent, which helps protect aquatic ecosystems. (Russell 2019)

Furthermore, managing the sludge produced during wastewater treatment is a critical aspect of the overall process. Sludge, a byproduct of the treatment process, must be effectively managed to prevent environmental harm. Sludge treatment typically involves anaerobic digestion, where microorganisms break down organic material in the absence of oxygen, producing biogas, which can be used for energy recovery. The treated sludge may then be dewatered, dried, and either disposed of in landfills or repurposed for agricultural use as fertilizer, provided it meets environmental standards. Efficient sludge management not only reduces the environmental footprint of wastewater treatment plants but also allows for the recovery of valuable resources like biogas. (Szeląg 2019)

Overall, wastewater treatment plants function through a series of well-established stages designed to remove a range of contaminants from wastewater. From the initial removal of large debris in the preliminary treatment stage to the final disinfection in tertiary treatment, each step plays a crucial role in ensuring that wastewater is adequately treated. Biological processes, such as activated sludge and nutrient removal techniques, are at the heart of most treatment plants such as Søholt and are essential for protecting water quality. Additionally, the management and treatment of sludge are vital for maintaining the sustainability of the entire process. Through ongoing advancements in technology and treatment methods, wastewater treatment plants continue to be a key component in safeguarding public health and the environment. (Szeląg 2019)

## **2.2 Hydrocyclones**

Hydrocyclones have been utilized since the late 20th century, characterized by a simple design that has seen minimal alteration over the years. Initially, these devices were found to be used primarily within the mining and paper industries, however, their usage has since expanded to include a variety of sectors, including chemical processing, food production, cement manufacturing, and petroleum extraction. Particularly, as mentioned in the introduction, hydrocyclones were integrated into wastewater treatment systems around the

1970s. A hydrocyclone functions as a sedimentation device that facilitates two distinct flow streams. It operates on the principle of enhanced gravity, effectively separating solid particles from liquids. The mechanism relies on centrifugal force generated by rotating the mixture within a conical cylindrical body. The hydrocyclone features two exits: one at the top for fine particles and another at the bottom for coarse particles. (Pericleous 1986)

While WWTPs like Søholt are designed to handle extreme weather conditions and above-average flows, their capacity can still be challenged under certain circumstances. As mentioned before Søholt lies relatively low comparing to groundwater which further challenges its capacity. It is challenged specifically, during periods of heavy rainfall, such as late winter and spring. The vulnerability of WWTPs like Søholt to hydraulic overload which had been a recurring issue means the need to address this challenge with strategies such as the use of storm tanks and additional rainwater basins. However, these measures alone have proven insufficient to fully mitigate the risks associated with extreme weather events. In response to this need for a more reliable solution at Søholt, the hydrocyclones were introduced as an alternative approach to ensure system stability even during the most extreme weather conditions, providing a greater sense of security and safeguarding the treatment plant's functionality under hydraulic stress. (Gemza 2022)

In the current context, where the emphasis is placed on waste reduction and the efficient utilization of resources, many industries are increasingly adopting technologies that minimize waste and consume low amounts of energy. Hydrocyclones are such technology, being low-maintenance and efficient. Therefore, there is a growing interest in exploring new applications for these devices. However, there are inherent drawbacks; hydrocyclones are engineered to operate under specific conditions tailored to industries, such as wastewater treatment. Their performance can vary significantly with fluctuations in flow parameters. Therefore, it is essential to consider the specific characteristics of the liquid being processed by the hydrocyclones and the conditions under which they operate. (Izquierdo 2022).

At the Søholt facility, the hydrocyclones are provided by SUEZ and are branded as inDENSE™. This technology was designed to extract low-quality sludge from the biological system, characterized by poor settling properties, while retaining heavier sludge that exhibits optimal settling ability. The effectiveness of this process can be monitored through the SVI, which is expected to remain stable throughout the year following the installation of the hydrocyclones. (Roche 2022)

Typically, the challenging period at Søholt begins in January and extends until the end of spring. As most CAS treatment plants contain a mixture of filaments, flocs, aggregates, and granules, hydrocyclones serve as a critical tool for differentiating high-quality sludge from lower-quality alternatives. (SCADA)

At Søholt, the sludge is introduced into the hydrocyclone through the inlet flow, where centrifugal force is applied. This force drives the denser, larger biomass particles toward the inner walls of the hydrocyclone, causing them to settle and flow downward into what will be referred to in this project as the underflow. The underflow is then redirected to the influent of the treatment plant and returned to the biological process tanks via a Bio-P tank which is an anoxic tank specifically designed for phosphorus removal. The lighter, less dense particles migrate towards the top of the hydrocyclone and are discharged through the overflow into a concentration tank for further processing. This process, repeated multiple times, enables the removal of filaments that negatively impact the settling characteristics of the sludge. By reinjecting the denser, thicker sludge into the system, the morphology of the sludge in the biological process tanks is altered, improving its settling properties and overall quality. As a result, the SVI is expected to remain more stable throughout the year, with fewer fluctuations caused by changes in climatic conditions. Typically, hydrocyclones are fed with return activated sludge (RAS) from the clarifiers, and their operation is facilitated by the presence of an anoxic zone, such as the Bio-P tank, which supports the denitrification process. Additionally, SUEZ recommends that the treatment plant be equipped with an effective sand removal system at the influent stage to prevent excessive "wear and tear" on the hydrocyclones and other equipment. (Roche 2022)

As mentioned above the hydrocyclones operate based on the principle of enhanced gravity, which facilitates the separation of solid, coarse particles from lighter, finer ones. The centrifugal force is employed to generate the necessary g-forces required to induce rotational motion within the hydrocyclone's conical cylindrical body. The separation occurs in the radial direction, where, as previously noted, the heavier, coarse particles are directed towards the wall and subsequently towards the bottom exit (underflow). Conversely, the finer particles move towards the top exit, forming the overflow. (Senfter 2021)

Several parameters must be considered when evaluating hydrocyclone performance, including particle size, which significantly influences separation efficiency. The pressure drop, which is directly related to the pumping requirements, is another crucial factor. This drop represents the energy required to rotate the incoming fluid and accounts for losses associated with the inlet and outlet designs. Even minor modifications to these designs can impact the overall efficiency of the system. (Senfter 2021)

Additionally, cyclone throughput, which is influenced by the pressure drop, plays a vital role in determining the amount of sludge a hydrocyclone can process at any given time. Generally, smaller particles require the use of smaller cyclones; however, this often necessitates the operation of multiple units parallel to achieve the desired processing capacity. (Pericleous 1986)

SUEZ offers skid-mounted stations that accommodate between two and five hydrocyclones, with Søholt utilizing a skid containing five units as can be seen in Figure 1.



Figure 1 Hydrocyclone station at Søholt WWTP

The hydrocyclone, despite its simplicity, consists of several key components. As illustrated in Figure 2, a typical hydrocyclone consists of 11 main parts. The primary inlet to the feed is connected to a vortex finder (1), which facilitates the rotational motion of the water, generating the necessary centrifugal force. The feed connection (1.1) supplies the cyclone with the incoming sludge. The overflow connection (1.2) allows the lighter sludge to be extracted as overflow. A screw tightening collar (1.3) functions as a clamp to secure the cyclone within the skid; this clamp must be tightened to withstand a pressure of 2.2 bar. Quick-release V-clamps (2) are used to enable quick disassembly and inspection of the cyclone body without the need for specialized tools. This feature proves particularly useful at Søholt, where blockages occasionally occur despite the presence of a macerator before the inlet, such as when packaging materials (e.g., contact lens packaging) obstruct the flow. The cyclone's body extension (3) serves as the structural foundation, complemented by the conical portion of the body (4). The spigot retaining ring (5) allows for efficient disassembly and inspection or cleaning of the underflow section. The snap-fit spigot cap (6) secures the underflow nozzle (6.1) in place, with the nozzle available in various

diameters. At Søholt, during the hydrocyclone assembly, the underflow nozzle initially had a diameter of 15 mm, which was later adjusted to 18 mm on November 4, 2024, in order to adjust to the colder process temperatures and therefore changes in the sludge. Finally, the removable spray reducer (7) protects the metal components from abrasion caused by the outlet jet of the dense sludge. This component is mandatory when there is no primary decanter, as is the case at Søholt. (Roche 2022)

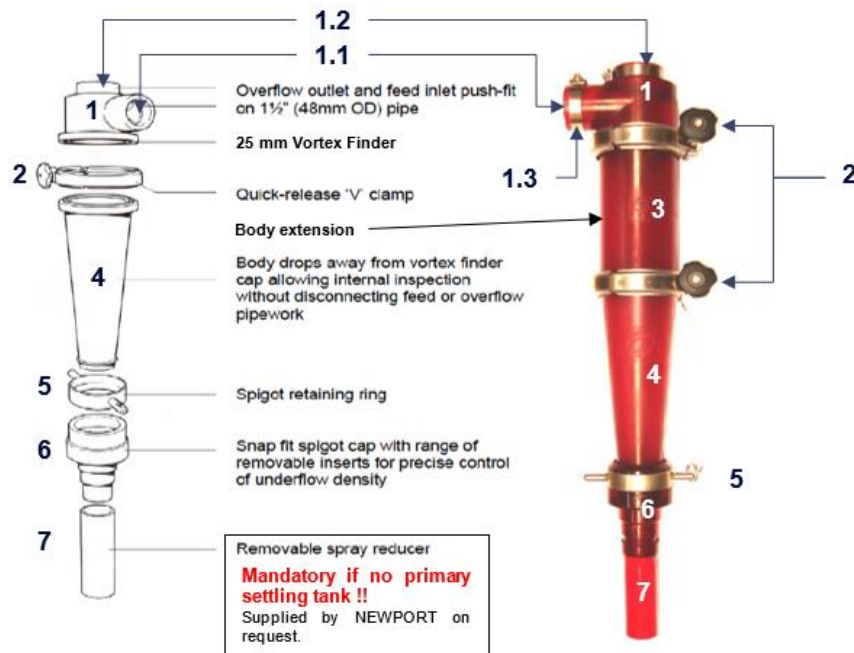


Figure 2 Schematic representation of a hydrocyclone and its components

### 2.3 Crucial parameters

The subsequent section of this thesis will look into a detailed analysis of the crucial parameters that significantly impact the performance of a conventional activated sludge wastewater treatment plant. Specifically, the focus will be on the sludge volume index and the required aerobic sludge age necessary to maintain optimal nitrification conditions. These parameters are crucial in optimizing the operational efficiency of a WWTP, as they influence both the settling characteristics of the activated sludge and the overall biological treatment process. Understanding the relationship between these factors and the application of hydrocyclones can offer valuable insights into improving sludge management and ensuring effective nutrient removal. Through this research, we

will assess how adjusting these parameters can ameliorate the performance and stability of the treatment system, thereby contributing to more sustainable wastewater treatment practices. (Theobald 2013)

### **2.3.1 Sludge volume index – SVI**

The sludge volume index is a widely used parameter, to assess the settleability of sludge in wastewater treatment systems. It plays a critical role in evaluating the efficiency and performance of activated sludge processes, such as those used in CAS systems. SVI provides insights into the physical characteristics of the sludge, such as its ability to compact and settle, which is essential for optimizing operational parameters like sludge age and ensuring effective nitrification. Most WWTPs including Søholt utilize activated sludge processes to treat municipal wastewater, making the proper care and optimization of these systems essential not only for the efficient operation of the plant, but also for the protection of the aquatic environment. One of the most critical components in managing activated sludge systems is the clarifier, which ensures that the sludge does not escape from the treatment process. For clarifiers to function effectively, the sludge must meet specific parameters, such as appropriate settability. (Chaubey 2021)

The methodology for determining the SVI is standardized in the DS/EN 14702-1:2006, a Danish Standard that outlines the correct procedures, for measuring the settleability of sludge suspensions. This standard is internationally recognized and applied in various fields, including municipal and industrial wastewater treatment plants, stormwater management, and water supply treatment facilities. By following the DS/EN 14702-1:2006 standard, operators can ensure that their measurements of sludge settleability are consistent, reliable, and accurate, providing critical data for managing and optimizing biological treatment processes. (DS/EN 14702-1:2006)

### **2.3.2 Nitrification**

The removal of large particulates via hydrocyclone could lead to more favourable conditions for the nitrifying microorganisms by reducing potential clogging or settling issues in the aeration tanks and improving overall hydraulic conditions.

This can directly support higher rates of ammonia oxidation and more effective nitrification which is a crucial process in a wastewater treatment plant. This is especially important for compliance, with environmental discharge standards and in reducing the risk of eutrophication in receiving water bodies such as the Gudenå river by the Søholt WWTP. By enhancing the solid-liquid separation in the final stages of wastewater treatment, the hydrocyclones are expected to bring several operational benefits like improved clarity and quality of the effluent that will lead to reducing the need for additional post-treatment processes (e.g., polishing filters or chemical treatment) that would otherwise be required to remove residual solids and particulates. This results in a streamlined treatment process with fewer operational steps, reducing both energy consumption and operational costs. One of the benefits is improved settling characteristics and reduced suspended solids, which means that the hydrocyclones are expected to ease the burden on downstream sludge management processes, making sludge dewatering and disposal more efficient and cost-effective. In addition to the anticipated improvements in sludge settling and nitrification efficiency the installation of the hydrocyclone station is also expected to enhance the hydraulic capacity of the wastewater treatment system. (Ruascelleda et al. 2011)

By improving solid-liquid separation and reducing the overall solids load, the hydrocyclone may increase the flow rate through the treatment process. Thereby optimizing the system's capacity to handle big influent loads which are especially felt during the winter and spring periods, during which the rain flow is bigger and when the snow melts and the groundwaters are at a dangerously high level. However, whilst this potential benefit is recognized, this thesis will not focus on hydraulic capacity, as the primary objectives are centred on the effects of the hydrocyclone on biological treatment performance, including nitrification and sludge settling characteristics. (Roche 2022)

Nitrogen is essential to all life as it is the fourth most abundant element in the biosphere. The nitrogen cycle is a big part of life, not just in wastewater treatment but also in our daily life. It is a series of processes that convert nitrogen between different chemical forms, making it available to living organisms and maintaining

the ecosystem balance. It begins with nitrogen fixation, where atmospheric nitrogen ( $N_2$ ) is converted into ammonia ( $NH_3$ ) or ammonium ions ( $NH_4^+$ ), a form that can be used by plants. (Ruascelleda et al. 2011)

This can occur biologically through nitrogen-fixing bacteria, or abiotically through lightning or industrial processes such as the Haber-Bosch method (this method will not be described further as it is not a part of this thesis). Once fixed, nitrogen undergoes nitrification, a two-step process in which ammonia is first oxidized into nitrites ( $NO_2^-$ ) by ammonia-oxidizing bacteria, and then nitrites are further oxidized into nitrates ( $NO_3^-$ ) by nitrite-oxidizing bacteria. Nitrates are the primary form of nitrogen that plants absorb through their roots during assimilation, incorporating it into organic compounds like amino acids and proteins. As Ruascelleda et al. explains, the organic matter decomposes, nitrogen returns to the soil through ammonification (or mineralization), where microorganisms break down organic nitrogen in dead animals, insects and plants, into ammonia, which is then available for reuptake or further processing. Some of the nitrates and ammonia in the soil can be reduced back to nitrogen gas ( $N_2$ ) or nitrous oxide ( $N_2O$ ) through denitrification, a process carried out by denitrifying bacteria in low-oxygen environments like the process tanks at Søholt. In addition, anammox is an anaerobic process that directly converts ammonium and nitrites into nitrogen gas, bypassing denitrification. Nitrogen can also be lost from the system through leaching, where soluble nitrogen compounds like nitrates move into groundwater, or volatilization, where ammonia gas is released into the atmosphere, particularly from soil or water with high pH (this must be taken into consideration when doing the mass balance at the WWTP). Together, these processes form a dynamic cycle that ensures nitrogen availability for plants and animals while maintaining a balance in ecosystems. Nitrogen levels in the environment are influenced by various factors, including soil conditions, moisture, temperature, and microbial activity. The processes in the cycle that happen on daily in the nature have been engineered to be able to replicate them at wastewater treatment plant to biologically treat the wastewater. These processes can be seen on Figure 3. (Ruascelleda et al. 2011)

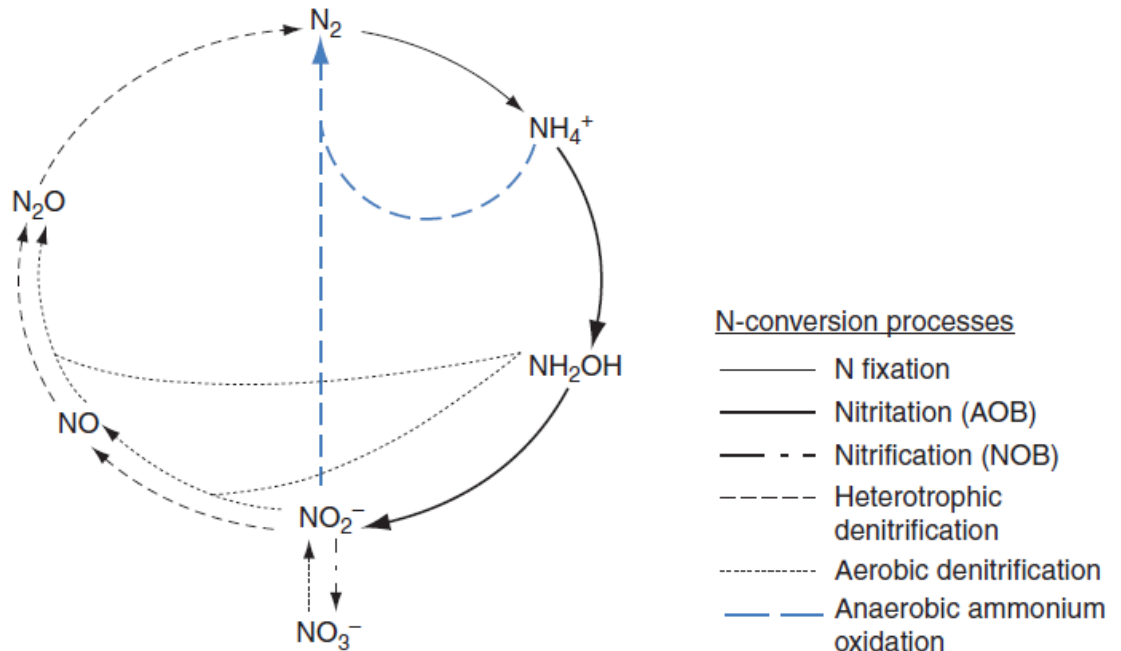
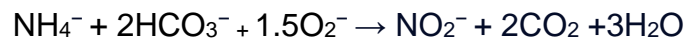


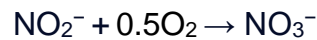
Figure 3 The nitrogen cycle

The formulas in the N-cycle are as follows

Nitration



Nitratation



Denitrification



It was around 1960 when the processes of nitrification and denitrification became widely used in wastewater treatment. The classic bioreactor systems, such as the one at Søholt, are configured to perform both nitrification and denitrification. At Søholt, these processes are controlled by set points in the SCADA system. The set points specify the operation of each aspect of the WWTP. If one was to take process tank four, that at Søholt is the most important tank as it is the last tank before the wastewater flows to the clarifiers, one would be met with many set points. (Ruascelleda et al. 2011)

The set points help operate the WWTP, for example, if nitrate is higher than 3,5 mg/l and at the same time the ammonium is under 3,5 mg/l or the nitrification

time (the time with aeration) has exceeded 70 minutes the aeration is turned off for a minimum of 25 minutes. More on the set points can be seen in appendix nr 2. As in most classic older wastewater treatment plants, at Søholt the wastewater first flows through an anaerobic bio-P tank (biological phosphorus removal tank), where no oxygen is present. Bacteria known as polyphosphate accumulating organisms (PAOs) release stored phosphorus from their cells and use the organic carbon in the wastewater as an energy source. Under anaerobic conditions, these PAOs cannot take up phosphorus, so instead, they release it to metabolize the available carbon. (Theobald 2013)

After going through the bio-P, the wastewater moves to the biological process tanks. As mentioned above, the biological process tanks at Søholt are combined nitrification-denitrification tanks, where both aerobic and anoxic conditions are carefully maintained to meet the specific requirements of the treatment process. In these tanks, nitrification which is the conversion of ammonia to nitrate occurs under aerobic conditions, while denitrification, which involves the reduction of nitrate to nitrogen gas, takes place under anoxic conditions. These two processes are closely interconnected with the sludge age, also referred to as biomass retention time. Sludge age is a critical factor because nitrifying bacteria grow relatively slowly and must be retained in the system for a sufficient period to ensure effective nitrification which leads to high treatment efficiency. Another key parameter that influences the nitrification-denitrification processes is aeration. During nitrification, dissolved oxygen (DO) must be adequately supplied to support the growth and activity of the nitrifying bacteria. The level of aeration directly affects the efficiency of the entire wastewater treatment process, as it controls the oxygen availability for the nitrification phase. Insufficient aeration can lead to incomplete nitrification, which in turn impacts the overall treatment performance. Additionally, the carbon/nitrogen (C/N) ratio plays a crucial role in denitrification. A suitable C/N ratio is necessary for denitrifying bacteria to reduce nitrate to nitrogen gas effectively. In many WWTPs, external carbon sources, such as methanol, are added to ensure an adequate C/N ratio for denitrification. However, at Søholt the hydrocyclones were introduced to increase the performance and the capacity while reducing the need for external carbon

supplementation, minimizing the addition of external chemicals while still maintaining effective nutrient removal. According to Ruascelleda et al. the simultaneous nitrification-denitrification (N/DN) tanks are more cost-effective and have been found to offer superior treatment performance. This is largely due to the development of concentration gradients within the system, where the anoxic process occurs in specific regions, typically within the anoxic zones of large nitrifying flocs. The coupling of these two processes in a single tank not only improves treatment efficiency but also reduces operational costs by minimizing the need for separate reactors and additional chemicals. (Ruascelleda et al. 2011)

### 2.3.3 Aerobic sludge age

The activated sludge process is one of the most widely used biological methods for treating municipal and industrial wastewater. It relies on a diverse community of microorganisms, primarily bacteria, to break down organic pollutants in aeration tanks where oxygen is continuously supplied or as in the case of Søholt alternated between anaerobic and aerobic. After aeration, the treated mixture flows into a secondary clarifier, where microbial solids settle. A portion of this settled sludge is returned to the aeration tank to maintain a concentrated biomass, while the remainder is removed as waste activated sludge. A key operational parameter in this system is sludge age, also known as solids retention time (SRT), which refers to the average time that microorganisms spend in the system. More specifically, aerobic sludge age refers to the duration that the biomass remains in the aerated zone of the process and is crucial for maintaining an effective balance of microbial populations. (Sidney 2018)

Aerobic sludge age is often expressed in days and is calculated using the formula:

$$ASA = \frac{M}{Q_w * f}$$

Where:

ASA stands for aerobic sludge age in days

M stands for total sludge mass in the aeration tank (kg)

$Q_w$  stands for daily sludge removed in kg per day

$f$  stands for fraction of time aerated in hours per day

This parameter is closely related to the aerobic nitrification retention time, as nitrifiers (slow-growing bacteria responsible for converting ammonia to nitrate) require longer residence times to establish in the system. In systems designed for enhanced nitrogen removal, maintaining the minimum aerobic sludge age is essential to ensure stable nitrification. However, there is a growing discussion around refining how sludge age is defined, particularly in systems using aerobic granular sludge. A proposed hypothesis suggests that if nitrifying organisms are primarily located in the dense core of microbial granules (rather than uniformly dispersed in the flocs), then their effective residence time should be based on the aerobic granule retention time, not the overall sludge retention time. This granule-focused approach could provide a more accurate representation of the microbial environment required for stable nitrification. (Yan et al. 2020)

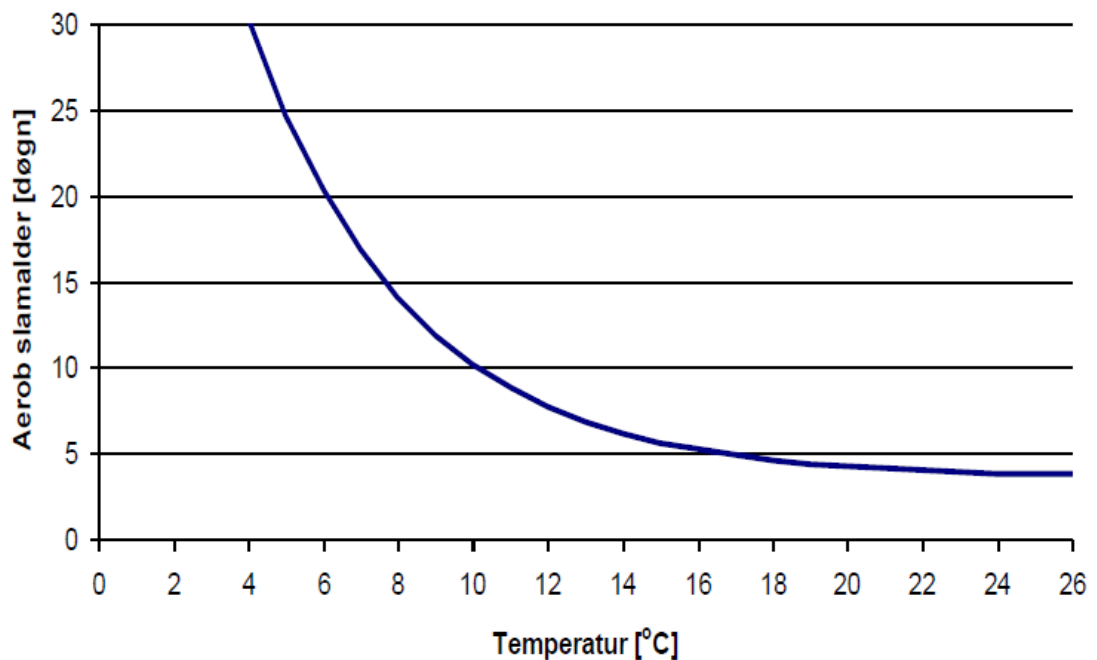


Figure 4 Sludge age is shown as a function of temperature across a 24-hour period

The formula for calculating granule retention time is:

$$GRT = \frac{G_f * M}{(C_f * Q_f) - (C_u * Q_u)}$$

Where:

GRT stands for granule retention time usually in days

$C_f$  stands for granule concentration in the feed in gram pr liter

M stands for total sludge mass in the system in kilograms

$Q_f$  stands for feed flow rate usually in liters per day

$C_u$  stands for granule concentration in the underflow usually in gram per liter

$Q_u$  stands for underflow rate in liters per day

This concept helps bridge the gap between process control and microbial ecology, offering a better way to target critical biological processes such as nitrification. Sludge age significantly influences the biological performance of the activated sludge system and is deeply connected to the operation of the hydrocyclone station at Søholt. Short aerobic sludge age favours the removal of readily biodegradable organic matter but can hinder nitrification. Typically, effective nitrification requires maintaining aerobic sludge ages between eight and fifteen days, depending on environmental conditions. On the other hand, excessively long sludge ages can reduce the activity of phosphorus-accumulating organisms, negatively impacting biological phosphorus removal. In addition to microbial dynamics, sludge age affects the physical characteristics of the sludge. Older sludge tends to be denser and more stable, improving settleability in the secondary clarifier. However, if sludge age is too high, settling properties can deteriorate, leading to poorer effluent quality. Thus, aerobic sludge age must be carefully managed to balance biological treatment efficiency and sludge handling performance. (Sidney 2018).

Recent research has explored the potential benefits of short sludge age systems, particularly for enhancing nitrogen removal and energy efficiency. In a study on high-rate denitrification, researchers found that systems operating at shorter sludge ages achieved nitrogen removal rates up to five times higher than those observed in conventional systems. This approach not only accelerates treatment

but also enhances the potential for energy and nutrient recovery from wastewater, positioning it as a promising alternative to traditional long-SRT systems (Tirkey et al. 2022).

Despite its historical success, the CAS process faces growing criticism for its inefficiencies and environmental impact. As highlighted in the work by Xiaoyuan Zhang and Yu Liu, CAS is an energy intensive process due to its reliance on continuous aeration. This leads to a significant energy footprint and limits the potential for achieving carbon-neutral operations which is a big focus going into the future. Moreover, CAS was not designed for resource recovery. As a result, essential elements like nitrogen, phosphorus, and organic carbon are often lost or converted into forms that cannot be easily reused. Additionally, the process generates large volumes of excess sludge, which poses further management and disposal challenges. These limitations have prompted calls for a shift toward new treatment paradigms that emphasize resource recovery, energy efficiency, and sustainability which means moving beyond the traditional pollutant-removal focus of CAS systems. (Zhang & Liu 2022)

### **3 METHOD**

This thesis will use a mixed-methods approach, integrating both secondary data analysis and laboratory experimentation. Pre-existing data gathered from Søholt WWTP reporting software will be analysed to identify broader patterns and trends related to the crucial parameters concerning SVI and nitrification. Additionally, laboratory experiments were conducted by a group of students from Aarhus university, in September of 2024, and October of 2024, and were continued in this thesis to further investigate aforementioned parameters, under controlled conditions, allowing for a deeper exploration and more precise data collection.

#### **3.1 Secondary data analysis**

As previously mentioned, this thesis will include an analysis of secondary data, which refers to data that has already been collected for purposes other than the current study. In this case, the data was originally gathered to monitor the

operation of the Søholt wastewater treatment plant. The data will be sourced from the Supervisory Control and Data Acquisition (SCADA) system used at the plant. SCADA systems provide real-time monitoring of various operational parameters, such as flow rates, chemical dosages, and other key performance indicators. The secondary data will provide valuable historical insights into the plant's operations and performance, particularly before and after the installation of the hydrocyclones. The specific time frame was different for each parameter. In order to capture relevant trends and variations in key parameters to compare before and after hydrocyclones the secondary data on SVI was five years and three years for aerobic sludge age. There was nothing on nitrification rates as such experiment was only done four times, two times in autumn of 2024 by the students from Aarhus University and twice the early spring of 2025 for this thesis. The analysis on historical data will serve to evaluate the impact of the hydrocyclones on the plant's operations and will contribute to a deeper understanding of its operational dynamics post-installation. Secondary data analysis offers several advantages. Firstly, it is economical, as the data has already been collected, eliminating the need for new data collection efforts and associated resource investment. Additionally, because the data is typically stored electronically, it is easily accessible and can be analysed efficiently. A further advantage is the breadth of the data, which often covers extensive time periods and a wide range of parameters, allowing for comprehensive analysis. Moreover, the data collection process is typically conducted by experts, ensuring professionalism and adherence to established standards. In the case of Søholt, the data is collected in accordance with Danish National Standards, and there is a large volume of data available, as it is essential for the daily operation of the treatment plant. (Boslaugh 2007)

As with everything there are limitations, and one common limitation of secondary data is that it was not originally collected with the researcher's specific questions in mind. However, in this case, this drawback is minimized. The data from Søholt is well-organized into distinct datasets, making it straightforward to locate and extract the relevant information for the current study. Overall, the decision to utilize secondary data for this project is well-founded. It not only provides a solid

background for subsequent primary data collection but also offers an opportunity to compare the plant's operations before and after the installation of the hydrocyclones. Furthermore, it provides a general overview of the plant's performance, highlighting both its strengths and areas for improvement. (Boslaugh 2007)

### **3.2 Supervisory Control and Data Acquisition - (SCADA)**

Supervisory Control and Data Acquisition systems play a critical role in the management and optimization of wastewater treatment facilities. It is a technology that comprises data acquisition, supervision and control over all processes. SCADA provides a centralized platform that allows operators like those working at Søholt to monitor, control, and automate various processes within the treatment plant. It combines real-time data acquisition, control functionalities, and data storage, offering significant advantages in terms of operational efficiency, data analysis, and remote monitoring. (Temido 2013) As mentioned, one of the primary functions of SCADA in wastewater treatment is to control the treatment processes. Wastewater treatment as mentioned above typically involves several stages, including preliminary treatment, primary and secondary treatment like biological processes, like activated sludge, which are the most significant for this thesis, and tertiary treatment. SCADA system integrates control of equipment at each stage of the process, such as pumps, valves, aeration systems, and chemical dosing systems.

For example, SCADA systems can control the flow of wastewater through different treatment units by adjusting the speed of pumps or opening and closing valves. In secondary treatment, SCADA is used to monitor and control the aeration process, which is essential for the growth of microorganisms that break down organic matter in the water which is necessary to control the nitrification and denitrification processes. (Sathika 2024)

The system can automatically adjust aeration rates based on real-time data, ensuring optimal conditions for microbial activity while preventing over-aeration, which could lead to energy wastage. SCADA systems excel in collecting real-time data from various sensors and devices distributed throughout the wastewater treatment plant. These sensors measure key parameters such as flow rates, pH,

turbidity, dissolved oxygen levels, temperature, and chemical concentrations, in case of Søholt it is data on O<sub>2</sub>, NO<sub>3</sub>, NH<sub>4</sub>-N, PO<sub>4</sub> and N<sub>2</sub>O as well as FeSO and NaAlO<sub>2</sub> used for the chemical treatment for the wastewater. The collected data is then transmitted to the SCADA system, which displays the information in a user-friendly graphical interface. (Clarke 2004)

Data collection is vital for understanding the performance of the treatment plant, identifying potential issues, and ensuring compliance with regulatory standards. Operators can monitor key performance indicators (KPIs) in real time, which enables them to make informed decisions quickly. For instance, if pH levels deviate from the optimal range, operators can use SCADA to automatically adjust the chemical dosing system to correct the imbalance, preventing costly damage to equipment and ensuring the treated water meets discharge standards. (Clarke 2004)

In addition to real-time monitoring, SCADA systems store historical data, allowing operators to track trends and make predictive analyses. This historical data is useful for long-term planning, performance evaluations, and troubleshooting. By analysing the past trends, operators can predict potential failures or identify inefficiencies in the treatment process, leading to more proactive maintenance and cost-saving measures. Historical data is also useful when conducting experiments like the one conducted for this thesis.

Another significant benefit of SCADA systems in wastewater treatment is remote monitoring and control. With SCADA, operators do not need to be physically present at the treatment plant to monitor or adjust operations. Remote access through the SCADA interface allows operators to control the system from anywhere, even outside regular working hours. This is especially useful for monitoring plants in remote or isolated locations, reducing the need for on-site personnel and enhancing the facility's responsiveness to emergency situations. The municipality of Silkeborg has a few of those remote locations besides Søholt, there are of course a few operators that drive onsite since not everything is updates to control over SCADA, but there are many things that can be done online like calibration of the process tanks sensors. (Temido 2013)

Automation is another key advantage of SCADA. The system can be programmed to automatically adjust processes based on pre-set conditions or

real-time data inputs without the need of the operator controlling the processes in real time. This reduces human error and increases operational efficiency. For instance, SCADA can automate the process of sludge removal when sludge levels reach a certain threshold, ensuring that the plant continues to operate smoothly without requiring manual intervention. Overall, SCADA systems are an integral part of modern wastewater treatment facilities. They enable operators to control complex processes, collect real-time and historical data, monitor key parameters, and automate systems for improved efficiency and reduced human error. The ability to remotely access and control the plant, coupled with the continuous data collection, enhances the overall operation of wastewater treatment, ensuring compliance, cost-efficiency, and environmental sustainability. As technology continues to evolve, SCADA will undoubtedly play an even more significant role in optimizing wastewater treatment processes and helping utilities meet increasing demands for water quality and sustainability. All SCADA at Søholt has been designed and implemented by a local programmer Palle Stauger that is to this day at Søholt and is now part of the modernization project. (Clarke 2004)

A short mention of PLC must be done in case of technology that are used at Søholt, that are interconnected with SCADA. PLC stands for Programmable Logic Controllers. They are used for automated control applications often as the middle step before data from the PLC goes to SCADA. (Sathika 2024)

### **3.3 Experimental research**

The experimental phase of this thesis involved two key procedures. First, the Sludge Volume Index (SVI) was measured to assess changes in the sludge characteristics over time, providing understanding of the settling properties and overall treatment performance. Additionally, nitrification experiments were conducted to evaluate the effectiveness of the hydrocyclone station at the wastewater treatment plant. These experiments aimed to determine whether recent process optimizations were resulting in improved nitrification rates, indicating enhanced treatment efficiency. (Denson 2023)

### 3.3.1 Sludge volume index

The Sludge Volume Index (SVI) is determined by observing the settling behaviour of a sludge sample over a 30-minute period, as prescribed by the DS/EN 14702-1:2006 standard. During this time, the sludge is allowed to settle under still conditions, and the volume of the settled sludge is measured. The SVI is then calculated as the volume of settled sludge in millilitres per liter of the original sludge sample. This measurement is a direct indicator of the sludge's settleability and provides valuable information, regarding the physical characteristics of the sludge, such as its compactness and the degree to which it can effectively settle within the treatment system. The SVI is an essential tool for monitoring and managing the operational performance of wastewater treatment facilities, as it can reveal potential issues such as bulking or poor settling, which could affect the overall efficiency of the treatment process. By following the precise methodology outlined in DS/EN 14702-1:2006, this measurement can be reliably performed, ensuring that the resulting data can be used to guide process improvements, including the optimization of parameters like aerobic sludge age and nitrification efficiency in CAS WWTPs. (DS/EN 14702-1:2006)

In order to perform SVI analysis one needs a graduated glass cylinder with a nominal capacity of 1000 mL and a diameter between 60 mm and 70 mm, as well as a scoop with a nominal capacity of 1 litre to take a representative sample of the sludge suspension. To perform a sludge volume index (SVI) test, one must begin by collecting a representative sample of the sludge suspension using a scoop. The sample is then immediately poured into a graduated cylinder, ensuring that the volume reaches the 1000 mL mark. Once the sample is in the cylinder, it must be left to settle undisturbed for 30 minutes. During this time, the sludge will naturally settle to the bottom, and it is crucial that the sample is not disturbed or shaken, as shaking could interfere with the settling process.

After the 30-minute settling period has passed, the next step is to measure the volume of the settled sludge. This measurement is taken at the surface level of the sludge and is recorded in millilitres. In some cases, if the initial volume of settled sludge exceeds 250 mL/L, the sample must be diluted before proceeding. To do this, a new sample is taken and mixed with water from the outlet of a clarifying tank in a 1:1, 1:2, or 1:3 ratio. The diluted sample is then allowed to

settle, and the volume of the settled sludge is measured again. The final sludge volume is calculated by multiplying the measured volume by the dilution factor (2, 3, or 4), depending on the dilution ratio used. This adjusted value gives a more accurate representation of the sludge volume for the SVI calculation.

The sludge volume index (SVI) is calculated using the following equation:

$$I_{sv} = \frac{V_s}{\rho T}$$

Where:

$I_{sv}$  is the sludge volume index in millilitres per gram

$V_s$  is the sludge volume in millilitres per litre after 30 min settling

$\rho T$  is the concentration of solids in sludge in grams per litre

This formula allows for the calculation of the SVI, which provides a measure of the sludge's settleability in relation to its concentration. The determination of the SVI following the DS/EN 14702-1:2006 standard is essential for evaluating the settling characteristics of sludge suspensions in various treatment processes. By following the standard's guidelines, the SVI can be accurately determined, providing valuable data for the optimization of wastewater treatment and sludge management systems. (DS/EN 14702-1:2006)

### 3.3.2 Nitrification

In order to perform the procedure, one needs to prepare a 10 mL  $\text{NH}_4^+$  solution with a concentration of 5 g N/L. Since the concentration is provided in terms of g N/L, it is important to take this into account when preparing the solution. To do so, the molar ratio between  $\text{NH}_4\text{Cl}$  and nitrogen (N) must be calculated as follows:

$$\frac{M_N}{M_{\text{NH}_4\text{Cl}}} = \frac{14,01 \frac{\text{g}}{\text{mol}}}{53,49 \frac{\text{g}}{\text{mol}}} = 0,262$$

$$c_{\text{NH}_4\text{Cl}} = \frac{5 \frac{\text{g N}}{\text{L}}}{0,262 \frac{\text{N}}{\text{NH}_4\text{Cl}}} = 19,08 \frac{\text{g NH}_4\text{Cl}}{\text{L}}$$

The required concentration of  $\text{NH}_4\text{Cl}$  is:

$$m = c \cdot V$$

$$19,08 \frac{g}{L} \cdot 0,01 L = 0,1908 g$$

Add demineralized water to make up the total volume to 10 mL and stir until the salt dissolves completely.

In order to carry out the procedure, one must first dilute all four batches of sludge (both underflow and inlet) by a factor of 4 using process water. For each batch, one needs to take 4 L of process water and allow it to settle for 60 minutes. After settling, one should set up a measuring glass with a funnel and coffee filter. Then, carefully pour the wastewater from the settled sludge from the process tank through the coffee filter to remove large particles. This filtering process must continue until 570 mL of clarified water is obtained. Once the clarified water is ready, one must mix 180 mL of sludge into the measuring glass and stir well. After stirring, one should transfer 750 mL of the mixture to a measuring cup. This process should be repeated for duplicates of both the inlet and underflow samples. For the next step, one needs to aerate the diluted sludge samples for nitrification measurement. To do so, an aquarium pump should be inserted into the measuring cups with the samples to aerate them for 4 hours. After the first 30 minutes of aeration, ammonium chloride should be added to the sample, ensuring the concentration reaches approximately 30 mg/L. In the case of this experiment the starting concentration was at about 25 mg/L. The sample must then be mixed thoroughly before the first sample is taken. During the aeration period, one must take samples at 30-minute intervals, resulting in a total of 8 samples. The ammonium concentration should be measured using the  $\text{NH}_4\text{-N}$  Kit every 30 minutes for the entirety of aeration period. Throughout the 4-hour aeration process, one must also measure and record the pH and temperature of the samples every 30 minutes. In order to collect and filter the samples taken every 30 minutes, one needs to use a syringe along with a 0.45  $\mu\text{m}$  filter.

### 3.3.3 Dry matter analysis

First a filter test with blind test for accuracy must be done. If one wants to ensure the accuracy of the filtration process for dry matter and ignition loss tests, one

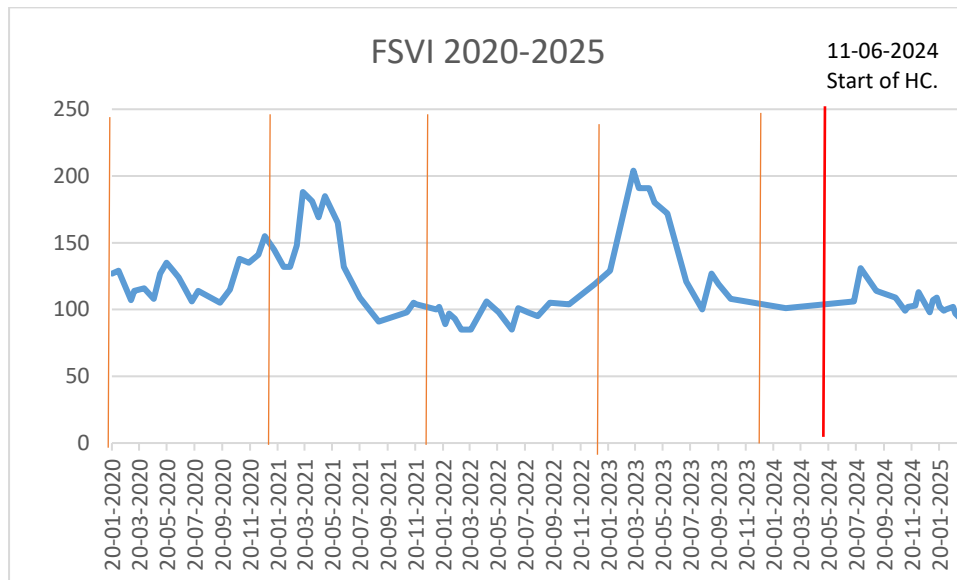
must first prepare a white circular filter paper for vacuum filtration. Before starting the actual analysis, a blind test is conducted to verify the reliability of the filtration results. For this, one must take three empty filters from different positions in the filter box (top, middle, and bottom) and weigh them together to assess the consistency of the filter materials. After weighing the filters, these blind test filters are washed under vacuum using 150 mL of demineralized water to eliminate any residual particles. These filters are then dried and placed in a muffle furnace to remove any moisture, providing a baseline for confirming the accuracy of the final results. The data from the blind test filters is not used directly in the experiment but serves as a reference to ensure the reliability of the actual sample data.

For the actual samples, one must first weigh the three filters used for the filtration process. Once weighed, 5 mL of the underflow or inlet sample is poured into the graduated cylinder and transferred over the filter under vacuum. The cylinder is washed with demineralized water until clean, the sample is also rinsed with distilled water for a few seconds. The water in the collection bottle is discarded. After filtration, the filters are carefully dried and placed in a muffle furnace. After drying, the filters are weighed again to determine the dry weight of the solids collected. It is important to weigh the filters before and after each step—before filtration, after drying, and once again after the furnace drying step—to ensure accurate data for the dry matter and ignition loss calculations. This process is repeated in triplicates for both the inlet and sieved inlet samples to ensure consistency in the results. Then the sieved sample analysis is done.

Regarding total solids (TS) analysis, one must first take 100 mL of both the inlet and underflow samples and sieve them carefully. The sample should then be scrubbed from the sieve with a spoon to ensure all solid material is properly collected. After sieving, the sample must be dried to remove excess moisture. Once dried, it is placed in a muffle furnace for further analysis. It is important to weigh the bowl before drying to account for the weight of the container. This will allow the weight of the dried material to be accurately determined by subtracting the container weight from the final mass after drying, leading to an accurate calculation of the total solids content. This process is also performed in triplicates for both the inlet and underflow samples to ensure reliable and consistent results.

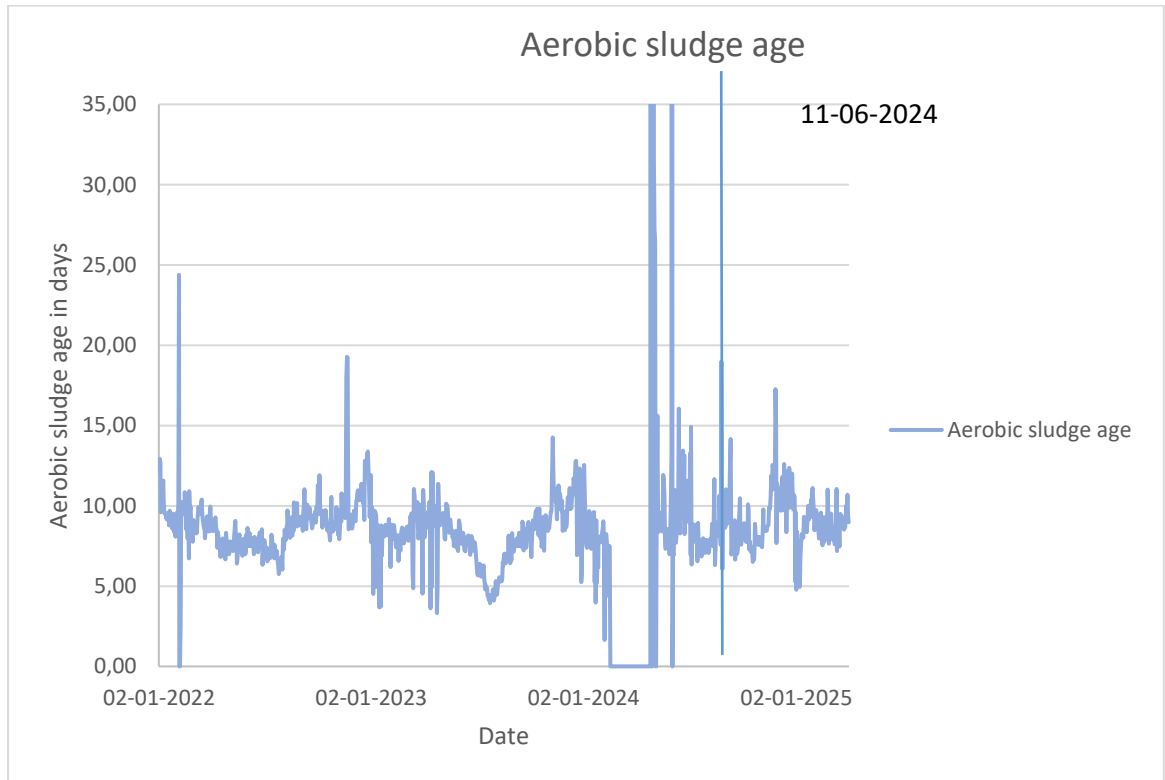
## 4 RESULTS

The results of this thesis include data on sludge settleability, sludge age, and ammonium removal following the installation of hydrocyclones at the Søholt Wastewater Treatment Plant. Hydrocyclones are increasingly used for sludge thickening and classification, impacting both sludge age and biomass retention (Izquierdo et al. 2022). Table 1 presents the sludge volume index (SVI) at Søholt over the past five years. In the accompanying graph, orange lines mark the end of each calendar year, while red lines indicate when the hydrocyclones became operational (June 6, 2024). The SVI values fluctuate seasonally, but no clear change is visible after the installation of the hydrocyclones. While hydrocyclones are designed to enhance sludge compaction and improve settling, their immediate effect may depend on site-specific factors such as operational settings and influent composition (SUEZ 2024).



Graph 1 SVI at Søholt over 5 years prior and after installation of hydrocyclones

Graph 2 shows that the aerobic sludge age has experienced minimal change since the hydrocyclones were installed. The light blue line indicates the installation date. Seasonal and annual variation is visible throughout the timeline. The fluctuations are more likely to be due to weather and seasonal changes. (Winther 1998)



Graph 2 Aerobic sludge age at Søholt three years prior and after installation of hydrocyclones

Graph 3 shows data from nitrification rate experiments, comparing samples from the inlet sludge (which in case of Søholt is the same as returned activated sludge) and the underflow. The results from autumn 2024 show a decline in nitrification rate, followed by an increase again in March 2025. This observed fluctuation aligns with seasonal temperature impacts on microbial activity involved in nitrification (Chen et al. 2020; Ruascelleda et al. 2011).

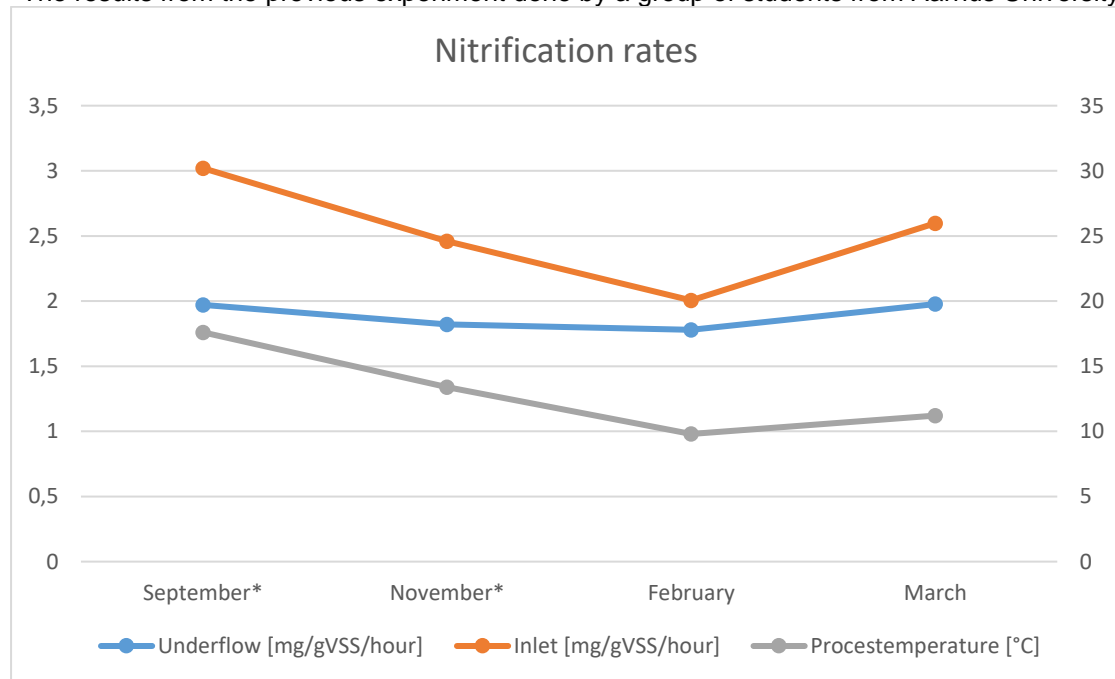
Table 2 presents the average ammonium removal rates from duplicates of each sample. The underflow shows a decrease in ammonium removal rate during autumn and February, with some recovery in March. This pattern can be influenced by sludge age and oxygen availability, as discussed in Innerebne et al.

and Tirkey et al. The inlet samples show a similar trend but less pronounced. The pH levels also varied across samples. In the underflow, pH decreased from 7.3 to 6.1 in February, and from 7.5 to 7.0 in March. In the inlet, pH decreased from 7.2 to 6.4 in February, and from 7.5 to 6.5 in March. pH fluctuations can significantly affect nitrification, as ammonia-oxidizing bacteria are sensitive to acidic conditions. (Henze et al. 1992)

Table 1 Nitrification rates

Month	Underflow [mg/gVSS/hour]	Inlet [mg/gVSS/hour]
September*	1,97	3,02
November*	1,82	2,46
February	1,78	2,01
March	1,98	2,60

\*The results from the previous experiment done by a group of students from Aarhus University



Graph 3 Nitrate rates

## 5 DISCUSSION

As previously noted, the inlet sample contained more activated sludge than the underflow sample, contrary to expectations. Hydrocyclones are designed to concentrate denser, more biologically active biomass, so this outcome may raise concerns regarding their performance (Riche 2022). Similarly, the nitrification rate experiments conducted during autumn showed a decline in ammonium removal

efficiency in the underflow sample, which further suggests suboptimal separation or reduced biological activity. However, it is important to acknowledge that external factors, such as environmental conditions and limited operational time, may have influenced these outcomes, or that the full effects of the hydrocyclones have yet to manifest. Given that the system at Søholt has been operational for less than a year, the timeframe may be insufficient to observe significant change. Temperature and seasonal fluctuations are known to significantly affect nitrification rates (Ruascelleda et al. 2011), and changes in pH, especially a significant drop observed in the underflow during February, may have impacted the activity of ammonia-oxidizing bacteria. These environmental variables are often difficult to isolate and control in full-scale systems. (Henze et al. 1992)

The implementation of hydrocyclones has not yet shown a noticeable effect on the sludge volume index. Instead, fluctuations in SVI appear to correlate more closely with seasonal changes and environmental conditions, such as groundwater levels and rainfall. This is consistent with studies that emphasize the influence of external environmental variables on SVI variability (Szelaq et al. 2019). Similarly, aerobic sludge age has remained relatively stable, which could reflect both the short operational period of the hydrocyclones and the influence of other operational changes at Søholt, such as the reactivation of the bio-P tank for biological phosphorus removal. Sludge age is known to significantly affect biological performance and could be masking the hydrocyclones early-stage effects. (Innerebne et al. 2018)

The nitrification experiments provided more nuanced insight into biomass activity. While it was anticipated that the underflow would be enriched with more active granules and thus exhibit higher nitrification potential, the inlet sample surprisingly contained more activated sludge. This may be an indication of incomplete or inefficient separation in the hydrocyclones (Chen et al. 2020), or simply a sign that the system requires more time to stabilize. Hydrocyclone performance is highly sensitive to design and operating conditions (Izquierdo et al. 2022), and suboptimal setup at Søholt may be contributing to the limited improvement observed thus far. As Senfter et al. pointed out, modified

hydrocyclones can be effective in sludge thickening, but only when their parameters are adjusted properly and when other factors are right. While the results at this stage are modest, they do not necessarily negate the potential benefits of hydrocyclones. Instead, they highlight the importance of long-term monitoring and process optimization. The impact of hydrocyclones might therefore be more visible after a longer period of operation, once system dynamics and sludge characteristics have adjusted.

## **6 LIMITATIONS**

One of the key limitations of this study lies in the relatively short duration since the installation of the hydrocyclones in June 2024. Given that the operational effects of hydrocyclones on wastewater treatment may require longer periods to fully manifest, the data collected within the first year may not accurately reflect the long-term trends. Additionally, the experiment conducted on nitrification rates by adding ammonium chloride may have been limited by an insufficient dose, potentially leading to an underestimation of nitrification potential and affecting the ability to draw definitive conclusions. The comparison of sludge volume index and aerobic sludge age data with values from three years ago may be compromised by differences in external variables such as influent characteristics, seasonal temperature changes, and operational adjustments. These changes complicate efforts to directly attribute the observed differences to hydrocyclone performance. Environmental and seasonal variations, such as fluctuations in rainfall or groundwater levels, were not controlled for. These factors can impact biological treatment efficiency and introduce additional variability in the results. Furthermore, procedural factors may have influenced experimental accuracy. For instance, settling tests are sensitive to handling conditions, if the sludge sample is overly shaken or experiences significant temperature differences from its surroundings, the settling behavior may be affected. To reduce such errors, measures such as equilibrating the sample temperature using a water-filled bucket is recommended, though these were not strictly standardized. These limitations must be considered when interpreting the results. Further studies with extended monitoring periods, optimized operational settings, and controlled experimental conditions would help strengthen the conclusions.

## 7 CONCLUSION

In conclusion, this thesis has demonstrated through analysis of SCADA data, historical performance records, and laboratory experiments that hydrocyclones may hold potential for optimizing key sludge parameters, such as sludge volume index, aerobic sludge age, and ammonium removal rates, at the Søholt Wastewater Treatment Plant. Theoretical research combined with practical data, including trends in SVI over the past five years, sludge age monitoring over the last three years, and nitrification rate experiments, suggest that the hydrocyclones have not yet produced a clear or consistent improvement in these parameters. While a reduction in SVI or enhanced sludge compaction was anticipated, the results showed no significant change following the installation of hydrocyclones. Similarly, the aerobic sludge age remained relatively stable, likely due to seasonal factors and operational changes unrelated to the hydrocyclones.

The nitrification rate data were less straightforward in terms of insights, with unexpected trends, such as higher activity in inlet sludge compared to underflow samples, raising questions about current hydrocyclone performance. Variations in pH and temperature appeared to influence these biological processes more directly than the separation effect of the hydrocyclones themselves. Furthermore, due to the short operational period since their installation (less than one year), the full effects of hydrocyclones may not yet be observable. Thus, while the data shows potential, the findings remain inconclusive. Continued monitoring over a longer period, including controlled comparative experiments and more detailed tracking of influent characteristics, will be necessary to assess the true long-term impact of hydrocyclones on sludge treatment efficiency in conventional activated sludge systems.

Ultimately, while this thesis set out to investigate the potential of hydrocyclones for optimizing sludge volume index and aerobic sludge age in a conventional activated sludge system, the results indicate that such optimization has not yet

been conclusively achieved, though longer-term evaluation may still reveal their full impact.

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## Nitrification apparatus and materials

- 4x 1L Measuring Glasse
- 4x Aquarium Pumps and Air Stones
- pH Meter
- NaOH and HCl for pH adjustment
- Bucket for collecting process water
- Coffee Filters
- 1L Measuring Glass
- Funnel
- Stirring Spoon for diluted wastewater
- Measuring Cup for removing wastewater after settling (60 min)
- Thermometer
- Stopwatch
- Wastewater Samples:
  - 3x 250 mL Underflow from Hydrocyclone (HC)
  - 3x 250 mL Inlet to HC
  - 8L Process Water
  - Stock Solution of  $\text{NH}_4$  (Ammonium chloride)
  - 20 mL Measuring Glass
  - $\text{NH}_4\text{Cl}$  (Ammonium chloride)
  - Small Spoon
  - Weighing Tray
  - 6x 10 mL Demineralized Water
  - $\text{NH}_4\text{-N}$  Kit
  - 1 mL Pipette and Pipette Tips
  - 0.45  $\mu\text{m}$  Filter
  - Plastic Syringes
  - Container for sample collection
  - Gloves

## Operational set points at Søholt WWTP

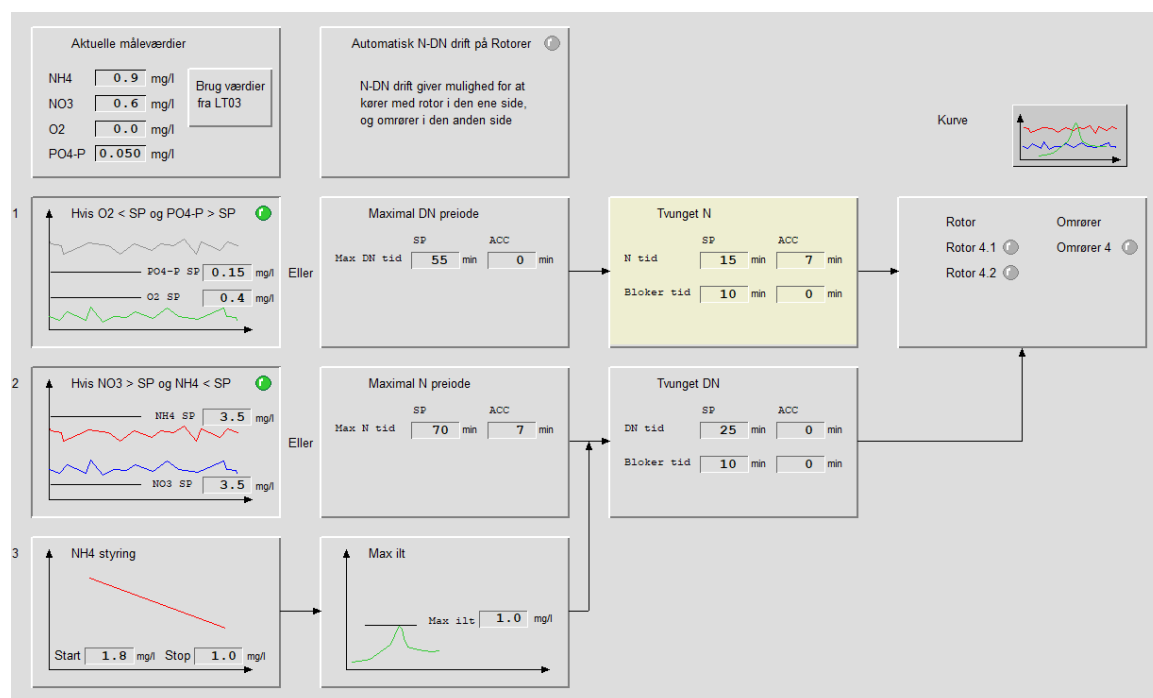


Figure 5 SCADA set points at Søholt

As seen on figure 5, which is the screenshot the wastewater treatment plant uses a control system to alternate between aerobic (N) and anoxic (DN) phases, based on real-time sensor values and predefined set points. Key measured parameters include ammonium (NH<sub>4</sub>), nitrate (NO<sub>3</sub>), oxygen (O<sub>2</sub>), and phosphate (PO<sub>4</sub>-P). The system evaluates specific conditions to trigger either nitrification (aerobic) or denitrification (anoxic) cycles. For example, if the oxygen level drops below 0.4 mg/l and the phosphate level exceeds 0.15 mg/l, the system initiates a denitrification phase. This DN phase can last up to a maximum of 55 minutes, unless overridden by a forced nitrification cycle. Similarly, if nitrate levels exceed 3.5 mg/l and ammonium is below 3.5 mg/l, it also triggers the DN phase.

To maintain process stability, the system includes forced cycles and blocking times. A forced nitrification (aerobic) phase is applied for at least 15 minutes (with a 7-minute adjustment window), and after this, a block time of 10 minutes ensures the DN phase doesn't immediately restart. On the other hand, a forced

denitrification period of 25 minutes is also possible, with a similar blocking period. Additional logic is based on NH<sub>4</sub> levels: when ammonium drops from 1.8 mg/l to 1.0 mg/l, the system regulates oxygen to a maximum of 1.0 mg/l to optimize conditions for nitrification. The entire process allows the rotor or mixer units to operate accordingly, switching between aeration and mixing modes to achieve efficient nutrient removal.

Nitrification experiment results

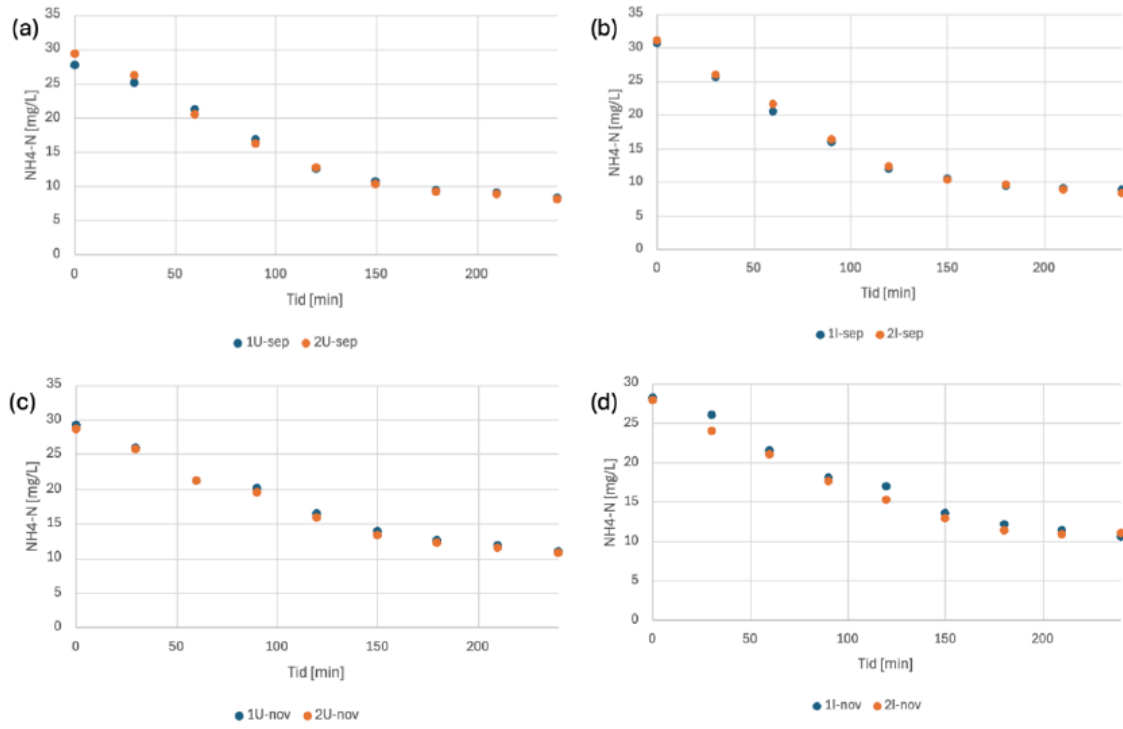


Figure 6 Nitrification rates done by the students from Aarhus University in autumn of 2024

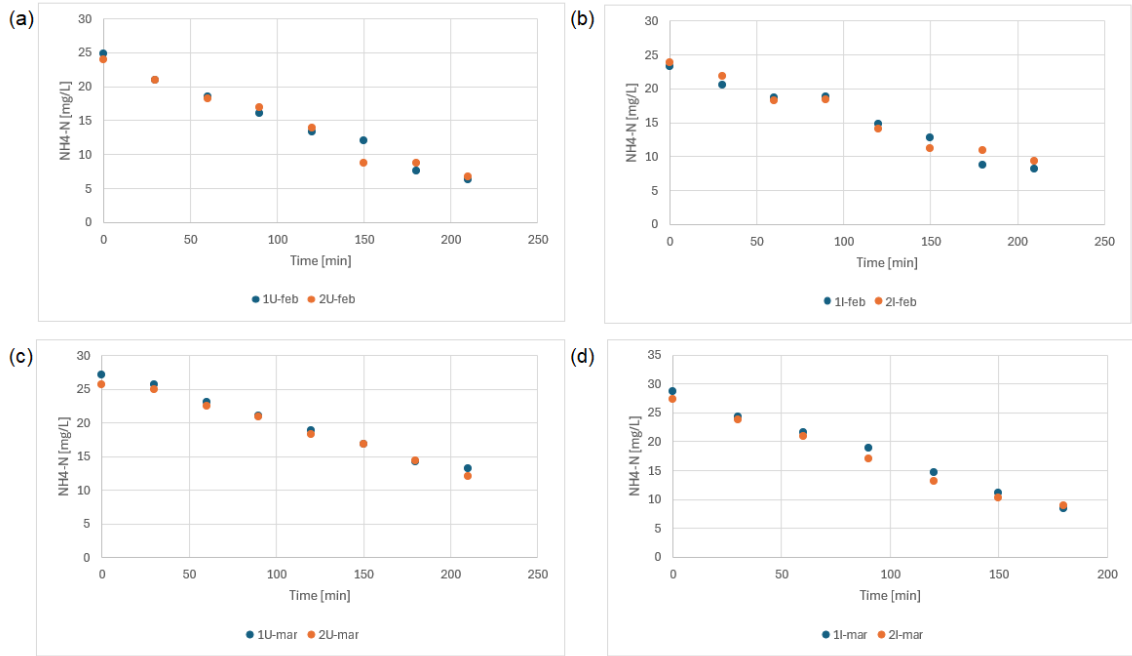


Figure 7 Nitrification rates done for this thesis early spring 2025

Figures 6 and 7 respectively show concentration of ammonium as a function of time rate. Figure 6 shows the results of the experiment of the students from Aarhus from September and November of 2024, and figure 7 shows the results from the experiments done for this thesis in February and March of 2025. The results in these graphs were used to calculate the nitrification rate in table number 1 in the results section.