ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

SIMULATION BASED OPTIMIZATION OF AERATION IN CAROUSEL REACTORS FOR SECURING NEW EU DISCHARGE REGULATIONS

M.Sc. THESIS

Irmak ÖZDEMİR

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

YENİ AB DEŞARJ YÖNETMELİKLERİNİN GÜVENCE ALTINA ALINMASI İÇİN KARUSEL REAKTÖRLERDE HAVALANDIRMANIN SİMÜLASYON TABANLI OPTİMİZASYONU

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To my beloved parents,

FOREWORD

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ABBREVIATIONS

AOB	**:**	Ammonia Oxidizing Bacteria
AS	**:**	Activated Sludge
ATP	**:**	Adenine Tri Phosphate
BNR	**:**	Biological Nutrient Removal
BOD	**:**	Biochemical Oxygen Demand
COD	**:**	Chemical Oxygen Demand
DO	**:**	Dissolved Oxygen
EBPR	**:**	Enhanced Biological Phosphorus Removal
EU	**:**	European Union
FST	**:**	Final Sedimentation Tank
IR	**:**	Internal Recirculation
JHB	**:**	Johannesburg
MLSS	**:**	Mixed Liquor Suspended Solids
MUCT	**:**	Modified UCT
NOB	**:**	Nitrite Oxidizing Bacteria
PAO	**:**	Polyphosphate Accumulating Organism
RAS	**:**	Return Activated Sludge
SBR	**:**	Sequencing Batch Reactor
SNdN	**:**	Simultaneous Nitrification Denitrification
SRT	**:**	Sludge Retention Time
TCOD	**:**	Total Chemical Oxygen Demand
TKN	**:**	Total Kjeldahl Nitrogen
TN	**:**	Total Nitrogen
TOC	**:**	Total Organic Carbon
TP	**:**	Total Phosphorus
TSS	**:**	Total Suspended Solids
VFA	**:**	Volatile Fatty Acid
VSS	**:**	Volatile Suspended Solids
WWT	**:**	Wastewater treatment
WWTP	**:**	Wastewater Treatment Plant

SYMBOLS

b_A	: Endogenous decay rate for autotrophs
b_H	: Endogenous decay rate for heterotrophs
b_{HD}	: Endogenous decay rate for denitrifying bacteria
C_S	: Biodegradable COD concentration
f_E	: Inert fraction of endogenous biomass
f_P	: Inert fraction of biomass in death-regeneration model
f_X	: Conversion factor for COD/VSS ratio
K_{NH}	: Half saturation concentration of ammonium
K_S	: Half-saturation constant for organic matter
μ_A	: Specific growth rate of autotrophic biomass
$\hat{\mu}_A$	: Maximum specific growth rate of active autotrophic biomass
q_A	: Specific removal rate of ammonia
S_{NH}	: Ammonium nitrogen concentration in the reactor
S_{NO}	: Oxidized nitrogen concentration
S_O	: Dissolved oxygen concentration
S_S	: Readily biodegradable COD concentration
X_A	: Autotrophic biomass concentration
X_{HD}	: Denitrifying bacteria biomass concentration
X_S	: Slowly biodegradable COD concentration

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SIMULATION BASED OPTIMIZATION OF AERATION IN CAROUSEL REACTORS FOR SECURING NEW EU DISCHARGE REGULATIONS

SUMMARY

This study delivers an in-depth assessment of a Wastewater Treatment Plant (WWTP) in the Black Sea Region by leveraging advanced process simulation tools. The main objective is to evaluate the design and operational efficiency of the plant to ensure it functions within optimal parameters and adheres to strict regulatory standards. Key metrics, including effluent quality, sludge production, and oxygen demands, were systematically compared with the plant's design documents and simulation results. The plant comprises multiple treatment units, such as a sand-grease chamber, Bio-P reactors, Carousel reactors, final clarifiers, and a disk filtration unit. Furthermore, the sludge management system utilizes mechanical thickeners and dewatering facilities to optimize sludge handling and processing, thereby enhancing overall treatment efficiency and sustainability. The simulations focused on the integrated operation of three Bio-P reactors, three Carousel tanks, and three final clarifiers, emphasizing their contribution to improving treatment efficiency and ensuring compliance with effluent quality regulatory standards. This study simulates the WWTP, assessing its design against performance metrics like effluent quality, sludge production, and airflow rate. The findings confirmed adherence to discharge limits for Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Nitrogen (TN), and Total Phosphorus (TP), validating the plant's operational effectiveness using actual wastewater data. The dissolved oxygen set-point, crucial for maintaining optimal biological activity, is regulated through simulation, particularly for the short carousel reactor used in the design. This approach ensures that the biological processes involved in nutrient removal are functioning efficiently, thereby enhancing the overall performance of the treatment plant. In carousel tanks with a low aspect ratio, dissolved oxygen (DO) levels play a critical role in the removal of nitrogen and phosphorus. These tanks are commonly used in biological nutrient removal (BNR) systems and optimizing aeration processes enhances the efficiency of nitrogen and phosphorus removal. Nitrogen removal relies on nitrification and denitrification processes. During nitrification, ammonium is oxidized to nitrite and then to nitrate, requiring high DO levels; low DO levels can reduce the nitrification rate, leading to ammonium accumulation. In the denitrification process, nitrate is reduced to nitrogen gas under anoxic (oxygen-free) conditions. Proper management of DO levels ensures the efficient execution of nitrification and denitrification processes, allowing simultaneous nitrification and denitrification (Simultaneous Nitrification-Denitrification, SND) to occur in the same tank. This reduces operational costs while enhancing nitrogen removal efficiency. Phosphorus removal depends on the activity of polyphosphate-accumulating organisms (PAOs). PAOs release phosphate under anaerobic conditions and take it up again under aerobic conditions. Proper management of DO levels ensures this cycle operates efficiently. Additionally, in simultaneous denitrifying phosphorus removal processes, nitrate is used as an electron acceptor, and low DO levels create the anoxic conditions necessary to enhance phosphorus removal efficiency. Therefore, optimizing DO levels in low aspect ratio carousel reactors enhances biological

processes and reduces energy consumption. Proper placement and adjustment of aeration equipment ensure DO levels are maintained within the desired ranges. Dynamic DO control systems, which monitor biological activity in real-time and automatically adjust DO levels based on this activity, further improve nitrogen and phosphorus removal efficiency.

Management of DO levels in low aspect ratio carousel tanks significantly improves nitrogen and phosphorus removal. This not only ensures compliance with environmental regulations but also increases energy efficiency, reduces operational costs, and contributes to sustainable wastewater management practices. These findings provide critical insights into the plant's operational strengths and areas for improvement. They serve as essential guidance for the appropriate dimensioning of bioreactors and the optimization of operational parameters, ensuring adherence to new EU discharge directives. The study not only confirms the plant's capability to meet stringent effluent quality standards but also underscores the importance of advanced simulation tools in achieving sustainable wastewater management. By leveraging these tools, the research highlights how simulation can be used to predict plant performance under various conditions, identify potential bottlenecks, and develop strategies to mitigate these issues before they impact the plant's operations. Furthermore, the study emphasizes the role of simulation in optimizing energy consumption within the WWTP. By accurately modeling the oxygen demands of the biological processes, the study provides recommendations for fine-tuning the aeration systems, which are among the most energy-intensive components of the treatment process. This not only helps in reducing operational costs but also contributes to the environmental sustainability of the plant by lowering its carbon footprint. The insights gained from this research are invaluable for the ongoing optimization of WWTPs, contributing to enhanced environmental protection and regulatory compliance in the region. The study's findings are particularly relevant in the context of increasing urbanization and industrial activities, which lead to higher volumes of wastewater requiring treatment. By demonstrating the effectiveness of simulation tools in improving plant performance, the research offers a blueprint for other WWTPs aiming to upgrade their systems and processes. This comprehensive evaluation using advanced process simulation tools provides a robust validation of the WWTP's design and operational strategies. It highlights the plant's strengths in meeting regulatory standards and identifies areas for further optimization. The study serves as a testament to the critical role of simulation in modern wastewater management, ensuring that plants not only comply with current regulations but are also prepared to meet future challenges in wastewater treatment. This research underscores the potential of advanced technologies in driving improvements in wastewater treatment, ultimately contributing to better environmental outcomes and sustainable water resource management.

YENİ AB DEŞARJ YÖNETMELİKLERİNİN GÜVENCE ALTINA ALINMASI İÇİN KARUSEL REAKTÖRLERDE HAVALANDIRMANIN SİMÜLASYON TABANLI OPTİMİZASYONU

ÖZET

Atıksu arıtımı, şehir ve endüstriyel su kaynaklarının yönetiminde kritik bir bileşendir ve çevreye bırakılan suyun düzenleyici standartlara uygun olmasını ve su ekosistemlerine zarar vermemesini sağlar. Atık suyun etkin bir şekilde arıtılması, halk sağlığının korunması, biyolojik çeşitliliğin sürdürülmesi ve su kütlelerinin genel bütünlüğünün korunması için esastır. Artan kentleşme ve sanayi faaliyetleri ile birlikte, üretilen atık su miktarı sürekli olarak artmakta ve dünya çapında arıtma tesisleri için önemli zorluklar oluşturmaktadır. Bu bağlamda, gelişmiş arıtma teknolojilerinin ve optimizasyon stratejilerinin benimsenmesi, atık su arıtma süreçlerinin verimliliğini ve sürdürülebilirliğini artırmak için zorunludur. Atık su arıtımı, fiziksel, kimyasal ve biyolojik süreçler dizisini içerir ve kirleticileri uzaklaştırarak kabul edilebilir kalitede çıkış suyu üretmeyi hedefler. Birincil arıtma genellikle askıda katı maddelerin ve yüzen malzemelerin çökelme ve eleme yoluyla uzaklaştırılmasını içerir. İkincil arıtma, aktif çamur sistemleri ve biyofilm reaktörleri gibi biyolojik süreçleri kapsar ve organik maddelerin ayrışmasını ve besin seviyelerinin azaltılmasını amaçlar. Üçüncül arıtma ise, azot, fosfor ve patojenler gibi belirli kirleticilerin uzaklaştırılmasına odaklanarak çıkış suyunu daha da cilalar ve sıkı deşarj standartlarını karşılamayı hedefler. Arıtmanın her aşaması, atık su arıtma tesisinin (AAT) genel etkinliğini sağlamada kritik bir rol oynar. Her bir aşama, kirleticilerin farklı türlerini hedefleyerek suyun kalitesini artırır ve ekosistemlere zarar verme potansiyelini azaltır. Bu süreçlerin etkin bir şekilde uygulanması, hem çevresel sürdürülebilirlik hem de halk sağlığı açısından büyük önem taşır. Bu araştırmanın birincil motivasyonu, biyolojik azot giderimi (BNR) sistemlerinde yaygın olarak kullanılan karusel reaktörlerdeki havalandırma süreciyle ilgili zorlukları ele almaktır. Havalandırma, biyolojik reaksiyonların verimliliğini ve genel işletme maliyetlerini etkileyen kritik bir bileşendir. Havalandırma sistemlerinin optimizasyonu, arıtma performansında, enerji tüketiminde ve düzenleyici standartlara uyumda önemli iyileştirmelere yol açabilir. Havalandırmanın doğru şekilde yönetilmesi, biyolojik süreçlerin etkinliğini artırarak daha düşük enerji tüketimi ve daha yüksek arıtma verimliliği sağlar. Bu bağlamda, karusel reaktörlerde havalandırmayı optimize etmek için gelişmiş simülasyon araçlarının geliştirilmesi ve uygulanması büyük önem taşımaktadır. Bu çalışma, bu araçları kullanarak havalandırma sistemlerini optimize etmeyi hedeflemekte ve bu sayede tesisin yeni AB deşarj düzenlemelerini karşılamasını sağlamaktadır. Simülasyon araçları, farklı senaryolar altında havalandırma sistemlerinin davranışını modellemeye ve tahmin etmeye olanak tanıyarak, sistemlerin verimliliğini artıracak stratejilerin belirlenmesine yardımcı olur. Enerji tüketimini azaltmak ve işletme maliyetlerini düşürmek için bu tür optimizasyon tekniklerinin kullanılması, sürdürülebilir atık su arıtma uygulamalarının geliştirilmesine katkıda bulunur. Sonuç olarak, bu çalışma, atık su arıtma süreçlerinin verimliliğini artırmak ve çevresel etkilerini minimize etmek için önemli bir adım olarak değerlendirilmektedir.

Bu çalışma, Karadeniz Bölgesi'nde çalışılan bir Atıksu Arıtma Tesisi'nin (AAT) gelişmiş proses simülasyon araçları kullanılarak kapsamlı bir değerlendirmesini sunmaktadır. Çalışmanın ana amacı, tesisin hem tasarım hem de işletme verimliliğini analiz etmektir. Atık su kalitesi, çamur üretimi ve oksijen ihtiyacı gibi temel ölçütler, tesisin tasarım belgeleri ve simülasyon sonuçlarına göre sistematik olarak değerlendirilmiştir. Tesis, kum-gres odası, Bio-P reaktörleri, Carousel reaktörleri, son durultucular ve disk filtrasyon ünitesi gibi çeşitli arıtma ünitelerini kapsamaktadır. Ayrıca, çamur yönetim sistemi mekanik yoğunlaştırıcılar ve susuzlaştırma tesisleri kullanarak çamurun taşınmasını ve işlenmesini optimize etmektedir. Simülasyonlar, üç Bio-P reaktörünün, üç Carousel tankının ve üç son durultucunun koordineli çalışmasına odaklanarak, bunların arıtma verimliliğini artırmadaki ve atık su kalitesine yönelik düzenleyici standartlara uygunluğu sağlamadaki rollerini vurgulamıştır. Boy/en oranı düşük karusel havuzlarda çözünmüş oksijen (DO) seviyeleri, azot ve fosfor gideriminde kritik bir rol oynar. Bu havuzlar, biyolojik besin maddesi giderimi (BNR) sistemlerinde yaygın olarak kullanılır ve havalandırma süreçlerinin optimize edilmesi, azot ve fosfor gideriminin etkinliğini artırır. Azot giderimi, nitrifikasyon ve denitrifikasyon süreçlerine dayanır. Nitrifikasyon sürecinde amonyum nitrite ve ardından nitrata oksitlenirken, yüksek DO seviyeleri gereklidir; düşük DO seviyeleri nitrifikasyon hızını azaltarak amonyak birikimine neden olabilir. Denitrifikasyon sürecinde ise nitrat, anoksik koşullarda azot gazına indirgenir. DO seviyelerinin dikkatli bir şekilde yönetilmesi, nitrifikasyon ve denitrifikasyon süreçlerinin verimli bir şekilde gerçekleşmesini sağlar ve aynı tankta hem nitrifikasyon hem de denitrifikasyonun gerçekleşmesine olanak tanır, bu da işlem maliyetlerini düşürürken azot giderim verimliliğini artırır. Fosfor giderimi ise polifosfat biriktiren organizmaların (PAOs) aktivitesine dayanır. PAOs, anaerobik koşullarda fosfatı serbest bırakır ve aerobik koşullarda tekrar alır. DO seviyelerinin uygun şekilde yönetilmesi, bu döngünün etkin bir şekilde işlemesini sağlar. Ayrıca, denitrifikasyon ile eş zamanlı fosfor giderimi süreçlerinde nitratın elektron alıcısı olarak kullanılması, düşük DO seviyelerinin anoksik koşulları sağlayarak fosfor giderim verimliliğini artırmasını sağlar. Bu nedenle, boy/en oranı düşük karusel reaktörlerde DO seviyelerinin optimize edilmesi, biyolojik süreçlerin etkinliğini artırır ve enerji tüketimini azaltır. Havalandırma ekipmanlarının doğru yerleşimi ve çalışma parametrelerinin ayarlanması, DO seviyelerinin istenilen aralıklarda tutulmasını sağlar. Dinamik DO kontrol sistemleri, reaktördeki biyolojik aktivitenin gerçek zamanlı izlenmesi ve DO seviyelerinin bu aktiviteye göre otomatik olarak ayarlanması, azot ve fosfor giderim verimliliğini artırır. Boy/en oranı düşük karusel havuzlarda DO seviyelerinin dikkatli yönetimi, azot ve fosfor gideriminde önemli iyileştirmeler sağlar. Bu, sadece çevresel düzenlemelere uyumu sağlamakla kalmaz, aynı zamanda enerji verimliliğini artırarak işletme maliyetlerini düşürür ve sürdürülebilir atıksu yönetimi uygulamalarına katkıda bulunur. Bu çalışma, AAT'nin kararlı durum simülasyonunu gerçekleştirerek tasarımını atık su kalitesi, çamur üretimi ve hava akış hızı gibi performans ölçütlerine göre değerlendirmiştir. Sonuçlar, Kimyasal Oksijen İhtiyacı (KOİ), Toplam Askıda Katı Madde (AKM), Toplam Azot (TN) ve Toplam Fosfor (TP) için deşarj limitlerine uygunluğu doğrulamış ve böylece tesisin operasyonel etkinliğini gerçek atık su verileri kullanarak teyit etmiştir. Optimum biyolojik aktivitenin sürdürülmesi için kritik olan çözünmüş oksijen ayar noktası, özellikle tasarımda kullanılan kısa karusel reaktör için simülasyon yoluyla düzenlenmiştir. Bu bulgular, tesisin operasyonel güçlü yönleri ve iyileştirme alanları hakkında kritik bilgiler sağlamaktadır. Biyoreaktörlerin uygun şekilde

boyutlandırılması ve operasyonel parametrelerin optimizasyonu için temel bir rehber görevi görerek yeni AB deşarj direktiflerine uyulmasını sağlar. Çalışma, tesisin katı atık su kalitesi standartlarını karşılama kapasitesini teyit etmekle kalmıyor, aynı zamanda sürdürülebilir atık su yönetiminin sağlanmasında gelişmiş simülasyon araçlarının öneminin altını çizmektedir. Bu araştırmadan elde edilen bilgiler, AAT'lerin devam eden optimizasyonu için çok değerlidir ve bölgede çevrenin daha iyi korunmasına ve mevzuata uygunluğa katkıda bulunur. Aynı zamanda bu çalışma, benzer tesislerin tasarım ve işletme stratejilerinin geliştirilmesine yönelik önemli ipuçları sunmaktadır. Özellikle tesisin enerji verimliliğinin artırılması ve işletme maliyetlerinin azaltılması konusunda elde edilen veriler, gelecekte yapılacak iyileştirmeler için yol gösterici olacaktır. Bu bağlamda, simülasyon araçları kullanılarak yapılan analizler, sadece mevcut performansın değerlendirilmesi ile sınırlı kalmayıp, aynı zamanda potansiyel iyileştirme alanlarının belirlenmesinde de önemli bir rol oynamaktadır. Bu sayede, tesisin uzun vadeli sürdürülebilirliği ve çevresel etkilerinin minimize edilmesi hedeflenmektedir. Simülasyonlar, farklı sıcaklık ve debi koşullarında tesisin performansını değerlendirmek için kullanılmıştır. Simülasyon sonuçları, tesisin çeşitli işletme koşulları altında bile yüksek verimlilikle çalışabileceğini göstermiştir. Özellikle, tesisin Kimyasal Oksijen İhtiyacı (KOİ), Toplam Askıda Katı Madde (AKM), Toplam Azot (TN) ve Toplam Fosfor (TP) konsantrasyonlarını etkin bir şekilde düşürebildiği ve bu değerlerin düzenleyici sınırlar içerisinde kaldığı belirlenmiştir. Genel olarak, simülasyon sonuçları çalışılan AAT'nin KOİ, AKM, TN ve TP konsantrasyonları açısından deşarj limitlerini karşılayabildiğini doğrulamıştır. Bu bulgular, tesisin tasarımını ve işletme stratejilerini doğrulamakta ve çevresel standartlara uyumu ve etkili arıtma performansını sağlamaktadır. Farklı sıcaklık koşulları arasında hava akışı gereksinimlerinde önemli değişiklikler göz önünde bulundurularak, hava akış hızlarını dinamik olarak ayarlayabilen ileri havalandırma kontrol sistemlerinin uygulanması önerilmektedir. Bu, biyolojik süreçlere verimli oksijen sağlanmasını ve düşük talep dönemlerinde enerji tasarrufu sağlanmasını garanti eder. KOİ, çamur üretimi ve havalandırma verimliliği gibi anahtar performans göstergelerinin (KPI'lar) sürekli izlenmesi kritik öneme sahiptir. Gerçek zamanlı izleme sistemlerinin ve adaptif yönetim uygulamalarının hayata geçirilmesi, işletme parametrelerinde zamanında ayarlamalar yapılmasına olanak tanıyarak deşarj standartlarına sürekli uyum ve optimal tesis performansı sağlar. Önerilen stratejilerin uygulanması ve tesisin süreçlerinin sürekli olarak optimize edilmesi ile çalışılan AAT, sürdürülebilir yüksek performans, çevresel uyum ve operasyonel dayanıklılık sağlayabilir. Bu çabalar, su kaynaklarının korunmasına ve sürdürülebilir atık su yönetimi uygulamalarının teşvik edilmesine katkıda bulunacaktır. Çalışmada elde edilen bulgular ve öneriler, sadece mevcut tesisin performansını optimize etmekle kalmayıp, gelecekte benzer projeler için de değerli rehberlik sunmaktadır. Bu bağlamda, simülasyon araçları kullanılarak yapılan analizler, tesisin operasyonel verimliliğini artırmak ve uzun vadeli sürdürülebilirlik hedeflerine ulaşmak için kritik öneme sahiptir. Simülasyonlar, hem günlük operasyonel kararlar hem de uzun vadeli stratejik planlama için vazgeçilmez bir araç olarak öne çıkmaktadır. Bu nedenle, sürekli olarak güncellenen ve geliştirilen simülasyon modelleri, tesisin karşılaşabileceği çeşitli senaryoları değerlendirmek ve optimal çözümler üretmek için kullanılmalıdır. Bu yaklaşım, çevresel etkileri minimize ederken, ekonomik verimliliği de maksimize etmeyi hedeflemektedir. Sonuç olarak, çalışılan AAT'nin kapsamlı bir şekilde değerlendirilmesi ve optimizasyonu, bölgedeki su kalitesinin korunmasına ve genel çevre yönetiminin iyileştirilmesine önemli katkılarda bulunacaktır

1. INTRODUCTION

Wastewater treatment is a critical component in the management of urban and industrial water resources, ensuring that water discharged into the environment meets regulatory standards and does not harm aquatic ecosystems. The effective treatment of wastewater is essential for protecting public health, preserving biodiversity, and maintaining the overall integrity of water bodies. With increasing urbanization and industrial activities, the volume of wastewater generated is continuously rising, posing significant challenges for treatment facilities worldwide. In this context, the adoption of advanced treatment technologies and optimization strategies is imperative for enhancing the efficiency and sustainability of wastewater treatment processes.

The treatment of wastewater involves a series of physical, chemical, and biological processes designed to remove contaminants and produce effluent of acceptable quality. Primary treatment typically involves the removal of suspended solids and floating materials through sedimentation and screening. Secondary treatment, which includes biological processes such as activated sludge systems and biofilm reactors, aims to degrade organic matter and reduce nutrient levels. Tertiary treatment further polishes the effluent, targeting the removal of specific contaminants such as nitrogen, phosphorus, and pathogens to meet stringent discharge standards. Each stage of treatment plays a crucial role in ensuring the overall effectiveness of the WWTP.

Despite the advancements in wastewater treatment technologies, several challenges persist. These include the need for energy-efficient processes, the management of emerging contaminants, and the reduction of greenhouse gas emissions associated with treatment operations. Innovations in wastewater treatment are increasingly focusing on the integration of advanced simulation tools, optimization techniques, and sustainable practices. Simulation-based optimization, in particular, has emerged as a powerful approach to enhance the design and operation of WWTPs, enabling the prediction and control of process performance under various scenarios.

The primary motivation for this research is to address the challenges associated with the aeration process in carousel reactors, which are widely used in biological nutrient

removal (BNR) systems. Aeration is a critical component of the treatment process, influencing the efficiency of biological reactions and the overall operational costs. The optimization of aeration systems can lead to significant improvements in treatment performance, energy consumption, and compliance with regulatory standards. This study aims to develop and apply advanced simulation tools to optimize aeration in carousel reactors, ensuring that the treatment plant meets the new EU discharge regulations for nitrogen and phosphorus. The importance of optimizing aeration systems cannot be overstated, given that aeration typically accounts for a significant portion of the energy consumption in WWTPs. Inefficient aeration can lead to higher operational costs and suboptimal treatment outcomes. By using simulation tools to model and predict the behavior of aeration systems under different operational conditions, this research seeks to identify strategies that can enhance the efficiency of these systems, thereby reducing energy consumption and improving overall plant performance. The ultimate goal is to develop a robust framework for the simulation-based optimization of aeration in carousel reactors, contributing to the advancement of sustainable wastewater treatment practices. The scope of this research encompasses the comprehensive evaluation of the wastewater treatment plant through advanced process simulation tools. The primary objective of the study is to analyze the plant's design and operating efficiency. To this end, important metrics like oxygen needs, sludge output, and effluent quality are methodically evaluated in comparison to the plant's design documents and simulation findings. The methodology emphasizes the importance of these components in ensuring compliance with effluent quality regulations and improving treatment efficiency by simulating the coordinated operation of three Bio-P reactors, three Carousel tanks, and three final clarifiers. This thesis is structured to provide a detailed account of the research conducted, starting with a comprehensive literature review on biological nitrogen and phosphorus removal processes, followed by the materials and methods section detailing the design and operational configuration of the WWTP. The literature review will cover the fundamental principles of biological nutrient removal, the role of aeration in wastewater treatment, and the advancements in simulation technologies for process optimization. The materials and methods section will describe the design specifications of the WWTP, including the configurations of the Bio-P reactors, Carousel tanks, and final clarifiers. It will also outline the simulation approach used to model the plant's operations and the parameters considered in the evaluation of its

performance. The results and discussion section presents the findings from the simulation studies, highlighting the plant's performance in meeting discharge limits for COD, TSS, TN, and TP. Optimizing DO levels in wastewater treatment processes is crucial for ensuring efficient nitrification and denitrification. Low DO concentrations can hinder nitrification, leading to the accumulation of ammonium (Boelee et al., 2012). To address this, dynamic DO control systems have been developed in real-time and adjust DO levels accordingly. These systems enhance the efficiency of biological processes, resulting in improved nitrogen and phosphorus removal, increased energy efficiency, reduced operational costs, and overall environmental sustainability (Wei et al., 2020). Studies have shown that controlling DO levels through dynamic systems can significantly enhance the operational efficiency of wastewater treatment plants and aid in compliance with environmental regulations (Ju et al., 2013). This section will also explore the impact of various operational strategies on the efficiency of the aeration system and the overall performance of the WWTP. By comparing the simulation results with the plant's design documents, the study aims to identify areas for improvement and recommend strategies for optimizing the treatment processes.

The conclusion and recommendations section offers critical insights into the plant's operational strengths and provides guidance for future improvements and compliance with new regulatory standards. This section will summarize the key findings of the research, discuss their implications for the design and operation of WWTPs, and suggest directions for future research. By addressing the challenges associated with aeration in carousel reactors, this research contributes to the development of more efficient and sustainable wastewater treatment practices, ensuring compliance with stringent environmental regulations and promoting the protection of water resources. Through a comprehensive analysis of the plant's operations and the application of state-of-the-art simulation techniques, this study seeks to contribute to the ongoing efforts to improve wastewater treatment practices and ensure the protection of the environment.

The primary aim is to assess the design and operational efficiency of the plant. This research provides a comprehensive evaluation of the Wastewater Treatment Plant in the Black Sea Region through advanced process simulation tools. Key metrics such as effluent quality, sludge production, and oxygen demands were systematically compared to the plant's design documents and simulation outcomes. The plant includes various treatment units such as a sand-grease chamber, Bio-P reactors, Carousel reactors, final clarifiers, and a disk filtration unit. The simulations concentrated on the coordinated operation of three Bio-P reactors, three Carousel tanks, and three final clarifiers, emphasizing their role in enhancing treatment efficiency and meeting regulatory standards for effluent quality. This study presents a simulation analysis of the WWTP, assessing its design against performance metrics such as effluent quality, sludge production, and airflow rate. DO levels need to be adjusted to support both nitrification and denitrification processes. The DO concentration should not be maintained at a fixed value but should be dynamic. The nitrification process requires the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-), which necessitates optimum DO levels. Low DO levels can reduce the nitrification rate, leading to ammonium accumulation. Dynamic DO control systems enable real-time monitoring of biological activity in the reactor and automatically adjust DO levels based on this activity. These systems enhance the efficiency of biological processes, resulting in significant improvements in nitrogen and phosphorus removal. The use of such control systems increases energy efficiency, reduces operational costs, and contributes to environmental sustainability.

This approach enhances both the operational efficiency of wastewater treatment plants and compliance with environmental regulations. Therefore, optimizing and dynamically managing DO levels is a critical strategy to improve the overall performance of the facility. Results validated the plant's operational efficacy using actual wastewater data by confirming compliance with discharge limitations for COD, TSS, TN, and TP. These results provide crucial information on the plant's operating advantages and are a vital source of assistance for properly sizing bioreactors in order to get new EU discharge directives.

2. LITERATURE REVIEW

2.1 Biological Nitrogen Removal

Biological nitrogen removal is a crucial process in wastewater treatment plants, involving mechanisms such as nitrification and denitrification to reduce nitrogen compounds in sewage effectively Ge et al. (2015). Traditional biological nitrogen removal processes, which include nitrification and denitrification, have been proven to be more efficient and cost-effective compared to physicochemical methods (Rahimi et al., 2020). Technologies for biological nitrogen removal, such as anammox and denitrifying bacteria, have been extensively studied and applied in wastewater treatment systems to enhance nitrogen removal efficiency (Ren et al., 2020). Recent advances in understanding microbial communities and biological nitrogen removal processes have shed new light on optimizing nitrogen removal in wastewater treatment systems (Peng & Zhu, 2006). The use of the nitrite pathway for biological nitrogen removal, involving nitrification and denitrification, has shown promise in achieving stable partial nitrification, which is crucial for efficient nitrogen removal (Jiang et al., 2022). Additionally, innovative microbial treatment processes, such as biofilm-microflocculation systems, have been developed to synergistically improve denitrification and phosphorus removal in wastewater treatment plants (Fuente et al., 2022). Moreover, the application of microbial electrochemical technologies and bioelectrochemical systems has emerged as a sustainable approach for nitrogen removal in marine and coastal environments, offering advantages such as low energy consumption and the ability to treat wastewater with low carbon-to-nitrogen ratios (Jin et al., 2020; Qian et al., 2016). In conclusion, biological nitrogen removal processes play a crucial role in wastewater treatment plants by effectively reducing nitrogen compounds through mechanisms like nitrification, denitrification, anammox, and innovative microbial technologies. Understanding and optimizing these processes are essential for sustainable and efficient nitrogen removal in wastewater treatment systems.
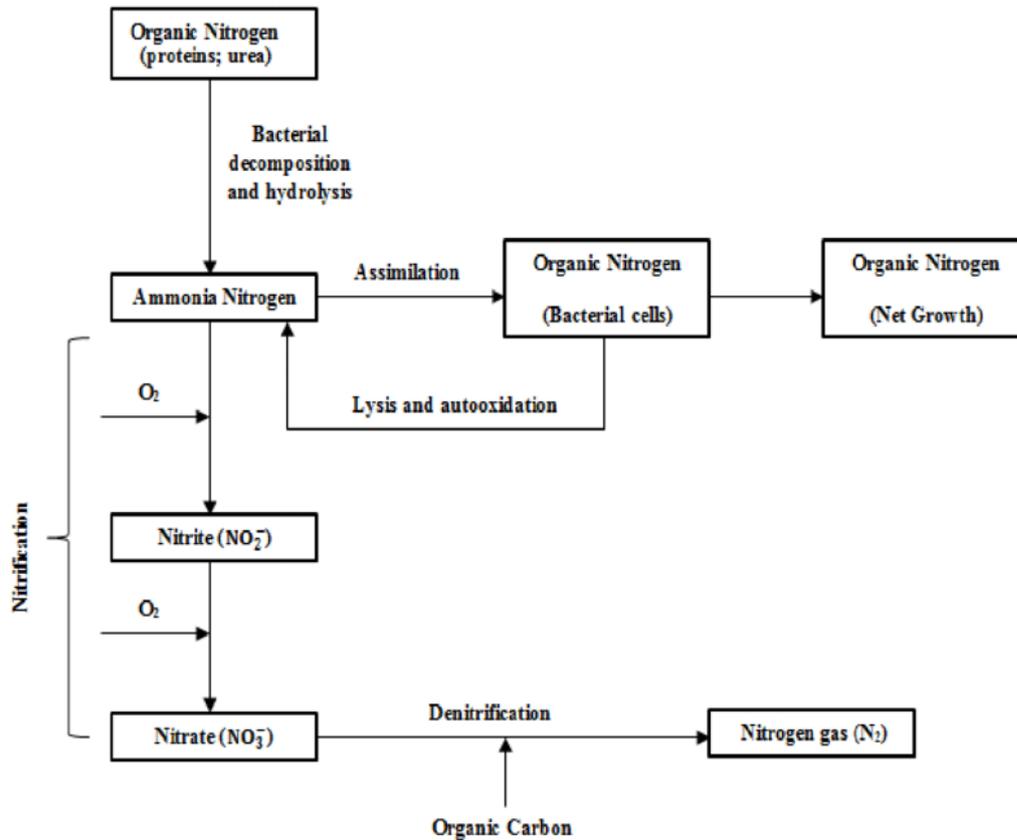
Figure 2.1. Biological nitrogen removal processes in wastewater treatment (Metcalf and Eddy, 2003).

2.1.1 Nitrification

Nitrification Nitrification is a crucial process in wastewater treatment plants that involves the conversion of ammonia to nitrites and then to nitrates by nitrifying bacteria (Zhao et al., 2013). This microbial process is essential for the removal of nitrogen compounds from sewage and plays a critical role in maintaining water quality standards (Zhao et al., 2013). The nitrification-denitrification process, which includes the subsequent reduction of nitrates to nitrogen gas, is a key mechanism for nitrogen removal in wastewater treatment systems (Zhao et al., 2013). This two-step process ensures that nitrogenous compounds, which are detrimental to aquatic life and can cause eutrophication, are effectively eliminated from treated wastewater. Research has indicated that nitrification-denitrification can be optimized by controlling environmental conditions and preventing further oxidation of nitrite nitrogen, leading to efficient nitrogen removal in polluted rivers (Jian et al., 2019). Key factors such as temperature, pH, and the concentration of dissolved oxygen must be carefully monitored and maintained within optimal ranges to enhance the activity of nitrifying

and denitrifying bacteria. By fine-tuning these parameters, wastewater treatment facilities can significantly improve their nitrogen removal efficiency, thereby ensuring compliance with stringent regulatory standards and protecting the health of aquatic ecosystems.

Additionally, innovative technologies, such as the simultaneous nitrification-denitrification (SND) process, have been shown to enhance denitrification rates by promoting the mediation of denitrification by phosphorus-accumulating organisms (PAOs) (Meyer et al., 2005). The SND process allows for the simultaneous occurrence of nitrification and denitrification in a single reactor, reducing the need for multiple treatment stages and consequently lowering operational costs. PAOs play a dual role in this process by not only aiding in nitrogen removal but also contributing to the removal of phosphorus, which is another critical pollutant in wastewater. Moreover, the selective inhibition of nitrite oxidation by chlorate dosing has been proven to enhance nitrogen removal efficiency by reducing aeration consumption during nitrification and saving organic matter requirements for subsequent denitrification and anammox processes (Xu et al., 2011). This approach not only improves nitrogen removal but also contributes to energy savings and process optimization in wastewater treatment plants (Xu et al., 2011). By selectively inhibiting the oxidation of nitrite to nitrate, chlorate dosing helps maintain higher concentrations of nitrite, which can be directly utilized by denitrifying bacteria. This results in a more efficient overall nitrogen removal process, reducing the need for external carbon sources and lowering the operational costs associated with aeration. In addition to these technological advancements, ongoing research is exploring the integration of microbial electrochemical systems with traditional nitrification-denitrification processes. These systems utilize bioelectrochemical reactions to facilitate the removal of nitrogen compounds, offering a sustainable and energy-efficient alternative to conventional methods. The potential for combining such innovative technologies with existing treatment processes holds promise for the future of wastewater treatment, making it more efficient, cost-effective, and environmentally friendly. Nitrification and denitrification are essential processes for nitrogen removal in wastewater treatment plants. By optimizing these processes through advanced technologies and careful control of environmental conditions, wastewater treatment facilities can achieve higher efficiency, lower operational costs, and improved compliance with environmental regulations. The integration of innovative approaches, such as SND,

chlorate dosing, and microbial electrochemical systems, represents a significant step forward in the field of wastewater treatment, contributing to the sustainable management of water resources and the protection of aquatic ecosystems.

2.1.1.1 Stoichiometry of nitrification

The nitrification process is carried out by aerobic autotrophic microorganisms. The electron source of the process is NH_3 and NO_2, electron acceptor is O_2, carbon source is CO_2, intermediate product is NO_2, and final product is NO_3. (Metcalf & Eddy, 2003). Nitrification consists of two stages in which ammonium is oxidised to nitrite and nitrite to nitrate. These stages are named as nitritation, where ammonium oxidation occurs, and nitration, where nitrite oxidation occurs, respectively.

The stoichiometry of nitritation and nitration is as follows (Sinha and Annachhatre, 2007):

$$NH_4^+ + 1.5O_2 \rightarrow 2H^+ + H_2O + NO_2^- + 58 - 84\ kcal \tag{2.1}$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- + 15.4 - 20.9\ kcal \tag{2.2}$$
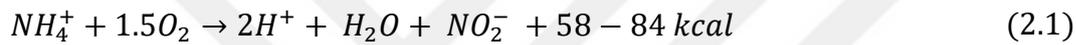
Equations (2.1) and (2.2) represent energy conversion. Equations (2.3) and (2.4) represent cell synthesis.

$$15CO_2 + 13NH_4^+ \rightarrow 10NO_2^- + 3C_5H_7NO_2 + 23H^+ + 4H_2 \tag{2.3}$$

$$5CO_2 + NH_4^+ + 10NO_2^- + 2H_2O \rightarrow 10NO_3^- + C_5H_7NO_2 + H^+ \tag{2.4}$$

Equation (2.3) and Equation (2.4) show CO_2 as the carbon source. The balance of CO_2 with carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-) in water is as in (2.5).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \tag{2.5}$$

The H+ ion produced in equations (2.1), (2.3) and (2.4) is used to form carbonic acid in equation (2.5). When the equations are rewritten to express this situation, equations (2.6), (2.7) and (2.8) are obtained.

$$NH_4^+ + 1.5O_2 + 2HCO_3^- \rightarrow 2H_2CO_3 + H_2O + NO_2^- + 58 - 84\ kcal \tag{2.6}$$

$$13NH_4^+ + 23HCO_3^- \rightarrow 8H_2CO_3 + 19H_2O + 10NO_2^- + 3C_5H_7NO_2 \tag{2.7}$$

$$NH_4^+ + 10NO_2^- + 4H_2CO_3 + HCO_3^- \rightarrow 10NO_3^- + C_5H_7NO_2 + 3H_2O \qquad (2.8)$$
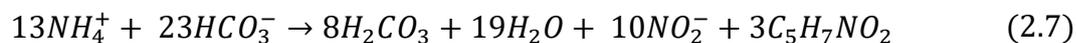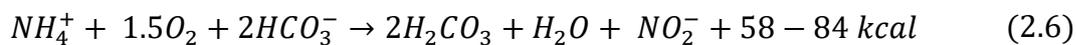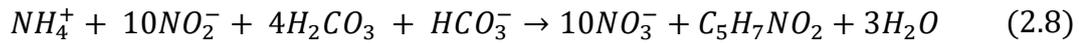
The energy obtained in equation (2.6), which expresses the energy conversion of nitritation, is used in equation (2.7), which contains the cell conversion of nitritation. These two equations can be synthesised. In the same way, a synthesis can be made between equations (2.2) expressing the energy conversion of nitration and (2.8) expressing cell synthesis. Thus, the general nitrification equation equation (2.9) is obtained (EPA 1975).

$$\begin{aligned} NH_4^+ &+ 1.83O_2 + 1.98HCO_3^- \\ &\rightarrow 0.021C_5H_7NO_2 + 0.98NO_3^- + 1.041H_2O \\ &+ 1.88H_2CO_3 \end{aligned} \qquad (2.9)$$
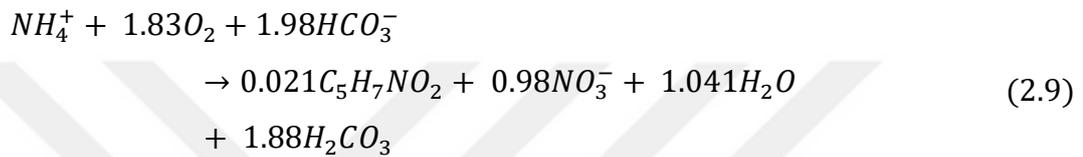
It is possible to see different molar coefficients in nitrification stoichiometry in the literature.

$$\begin{aligned} NH_4^+ &+ 1.731O_2 + 1.962HCO_3^- \\ &\rightarrow 0.038C_5H_7NO_2 + 0.962NO_3^- + 1.077H_2O \\ &+ 1.769H_2CO_3 \end{aligned} \qquad (2.10)$$
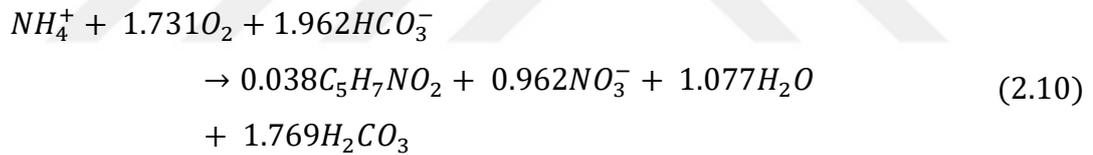
According to Equation (2.10), 3.96 mg O_2 is consumed, 7.01 mg alkalinity is required, 0.16 mg inorganic carbon is used, and 0.31 mg cell is produced for 1 mg NH_4^+-N conversion in nitrification reaction (Metcalf & Eddy, 2003).

In nitrification, oxygen is involved in transporting electrons released during ammonium and nitrite oxidation from the bacterial cell (Gerardi, 2002).

There are many intermediate products formed during nitrification such as hydroxylamine (NH_2OH). Since these products are transformed in a short time, they are not expressed in the reactions describing nitrification (Gerardi, 2002).

In the nitrification process, nitrite oxidation occurs faster than ammonium oxidation. For this reason, nitrite is temporarily present in the medium. This is due to the relatively low minimum substrate concentration (Smin) values for the steady-state biomass of nitrite-oxidising bacteria and the relatively high rate of substrate utilisation (Sinha and Annachhatre, 2007).

2.1.1.2 Kinetics of nitrification

Numerous environmental variables, including temperature, pH, toxicity, and the concentration of dissolved oxygen, influence the rate of nitrification. The conversion rate of organic nitrogen (Org-N) and ammonium nitrogen (NH4-N) to nitrate (NO3$^-$) is directly linked to the growth rate of autotrophic organisms. Similar to heterotrophic bacteria, the growth kinetics of autotrophic microorganisms are described using the Monod equation.

$$\mu_A = \hat{\mu}_A . \frac{S_{NH}}{K_{NH} + S_{NH}} \tag{2.11}$$

In this context, μ_A represents the specific growth rate (d^{-1}) for autotrophs, and $\hat{\mu}_A$ signifies the maximum specific growth rate (d^{-1}). Furthermore, S_{NH} and K_{NH} indicate the concentration of the rate-limiting substrate (mg l^{-1}) and the half-saturation constant for this substrate (mg l^{-1}), respectively.

The rate-limiting substrate for ammonia-oxidizing bacteria (AOB) is identified as ammonia, whereas for nitrite-oxidizing bacteria (NOB), nitrite serves as the limiting factor. The conversion of ammonium nitrogen (NH4-N) to nitrite (NO2$^-$) occurs at a significantly slower pace compared to the transformation of nitrite to nitrate (NO3$^-$). Additionally, nitrite produced during the nitrification process is rapidly oxidized to nitrate by NOBs in the presence of oxygen. As a result, the transformation of ammonia to nitrite is deemed the bottleneck in the nitrification process. Given that nitrate accumulation is unlikely in a steady-state system due to the aforementioned factors, the rate-limiting substrate mentioned in equation (2.11) is recognized as the concentration of ammonium nitrogen (mg l-l). Consequently, SNH is regarded as the concentration of ammonia (mg l-l).

Moreover, since the presence of oxygen is the key factor for nitrification to take place, a double Monod kinetic model is sometimes used to account for the dissolved oxygen concentration in the reactor (Ergas and Aponte-Morales, 2014, p. 130).

$$\mu_A = \hat{\mu}_A . \frac{S_{NH}}{K_{NH} + S_{NH}} . \frac{S_O}{K_{OA} + S_O} \tag{2.12}$$

Equation (2.12) presents the double Monod equation, in which S_O and K_{OA} represent the concentration of dissolved oxygen (mg l^{-1}) and the half-saturation constant for dissolved oxygen (mg l^{-1}) for autotrophs, respectively.

For autotrophs, microbial growth adheres to first-order reaction kinetics and is determined using XA (mg l-1) and μA (d-1), which represent the concentration of autotrophic biomass and the specific growth rate of autotrophs, respectively.

$$\frac{dX_A}{dt} = \mu_A . X_A = \hat{\mu}_A . \frac{S_{NH}}{K_{NH} + S_{NH}} . X_A \tag{2.13}$$

Biomass growth can also be represented through the stoichiometric conversion expression of substrate removal, as shown in the following equation.

$$\frac{dX_A}{dt} = -Y_A . \frac{dS_{NH}}{dt} \tag{2.14}$$

Endogenous decay for autotrophic microorganisms is also expressed using first-order reaction kinetics, with the equation utilizing the concentration of autotrophic biomass, represented as X_A (mg l^{-1}), and the decay constant, represented as b_A (d^{-1}), to calculate the decayed biomass.

$$\frac{dX_A}{dt} = -b_A . X_A \tag{2.15}$$

Taking into account all of the aforementioned factors, the variation in nitrifying bacteria over time can be described by integrating both growth and decay kinetic reactions, as depicted in equations (2.13) and (2.15), respectively.

$$\frac{dX_A}{dt} = \mu_A . X_A - b_A . X_A = \hat{\mu}_A . \frac{S_{NH}}{K_{NH} + S_{NH}} . X_A - b_A . X_A \tag{2.16}$$

The specific yield for autotrophs, denoted as YA, is determined by the ratio of the quantity of biomass produced to the quantity of substrate eliminated. Consequently, the correlation between biomass growth and substrate removal can be articulated as follows.

$$\frac{dS_{NH}}{dt} = -\frac{\mu_A}{Y_A} \cdot X_A = -\frac{\hat{\mu}_A}{Y_A} \cdot \frac{S_{NH}}{K_{NH} + S_{NH}} \cdot X_A \tag{2.17}$$

Equation (2.17) can also be expressed using specific removal rate of ammonia, which is denoted by q_A (mg N $\cdot$ mg VSS^{-1} d^{-1}).

$$q_A = \frac{\mu_A}{Y_A} = \frac{\hat{\mu}_A}{Y_A} \cdot \frac{S_{NH}}{K_{NH} + S_{NH}} \tag{2.18}$$

Utilizing equation (2.18), the removal of the substrate can be articulated as follows:

$$\frac{dS_{NH}}{dt} = -q_A \cdot X_A \tag{2.19}$$

The oxidation of 1 mole of ammonium nitrogen results in the production of 1 mole of nitrate nitrogen. Consequently, the relationship between the concentration of oxidized nitrogen (S_{NO}) and the concentration of ammonium (S_{NH}) can be expressed as follows (Orhon and Artan, 1994).

$$\frac{dS_{NO}}{dt} = -\frac{dS_{NH}}{dt} \tag{2.20}$$

Furthermore, the consumption of oxygen (which serves as the electron acceptor in the nitrification process) can also be represented in terms of growth and decay mechanisms by employing equation (2.20).

$$\frac{dS_O}{dt} = -\frac{4.57 - f_X Y_A}{Y_A} \mu_A X_A - (1 - f_E) b_A f_X X_A \tag{2.21}$$

$$\frac{dS_O}{dt} = -(4.57 - f_X Y_A) q_A X_A - (1 - f_E) b_A f_X X_A \tag{2.22}$$

where f_E is the inert fraction of the biomass in endogenous respiration approach.

2.1.2 Denitrification

Denitrification is a crucial process in wastewater treatment plants that involves the conversion of nitrates into nitrogen gas or other gaseous compounds, aiding in the removal of bioavailable nitrogen from wastewater (Law et al., 2012). This process is essential for reducing the nitrogen load in treated effluent, which, if left unchecked, can lead to eutrophication in receiving water bodies, causing severe ecological damage. Understanding the fundamental reactions responsible for nitrous oxide (N_2O) production in denitrification processes is essential for reducing N_2O emissions from wastewater treatment systems through improved plant design and operation (Law et al., 2012). Nitrous oxide is a potent greenhouse gas, and its emissions from wastewater treatment processes contribute significantly to climate change. Models have been developed to simulate electron competition among nitrogen oxides reduction and N_2O accumulation in denitrification, providing insights into optimizing denitrification processes in wastewater treatment (Pan et al., 2013). These models help in predicting the conditions under which N_2O is likely to be produced, allowing for the development of strategies to minimize its formation. For instance, controlling the availability of carbon sources and maintaining optimal redox conditions can significantly reduce N_2O emissions. Efforts have been made to model N_2O emissions from full-scale wastewater treatment plants, emphasizing the importance of addressing nitrogen removal processes like denitrification in plant design and operation (Ni et al., 2013). Such modeling efforts are crucial for developing comprehensive mitigation strategies that ensure both effective nitrogen removal and reduced greenhouse gas emissions.
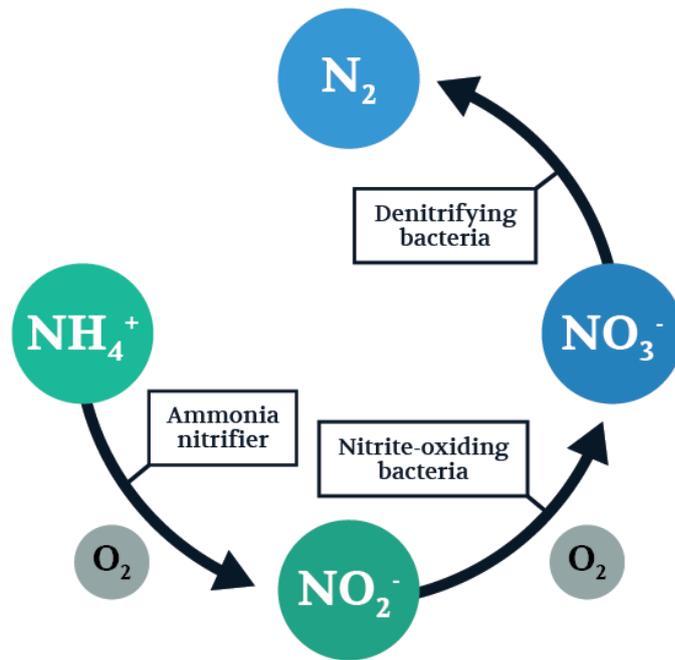
Figure 2.2. Reaction route of conventional nitrification and denitrification.

Denitrification plays a key role in nitrogen removal from wastewater, and its optimization can contribute to sustainable operation and improved effluent quality in wastewater treatment plants (McCarty, 2018). By fine-tuning operational parameters such as dissolved oxygen levels, carbon source addition, and hydraulic retention time, wastewater treatment facilities can enhance the efficiency of the denitrification process. Additionally, microbial communities, including denitrifying bacteria, are essential in driving denitrification rates in wastewater treatment systems (Saarenheimo et al., 2017). The composition and activity of these microbial communities are influenced by various environmental factors, and understanding these dynamics is key to optimizing denitrification. Studies have shown that denitrification can be enhanced by utilizing external carbon sources, such as fermentation liquid from food waste, to boost the denitrification process in wastewater treatment plants (Zhang et al., 2016). External carbon sources can provide the necessary electron donors for the reduction of nitrates to nitrogen gas, thus improving the overall efficiency of the process. Furthermore, the use of innovative technologies like biofilm-microflocculation systems can synergistically improve denitrification and phosphorus removal in wastewater treatment plants, highlighting the importance of advanced treatment methods for nitrogen removal (Jiang et al., 2022). These systems combine the benefits of biofilm processes with microflocculation, enhancing the physical removal of

nitrogen and phosphorus while promoting biological nutrient removal. In addition to these advancements, integrating anammox (anaerobic ammonium oxidation) processes with traditional denitrification can further enhance nitrogen removal efficiency. Anammox processes convert ammonium and nitrite directly into nitrogen gas under anoxic conditions, offering a complementary pathway to traditional denitrification. This integration can reduce the need for external carbon sources and lower operational costs while maintaining high nitrogen removal efficiency.

Denitrification is a critical process in wastewater treatment plants that plays a significant role in nitrogen removal. By optimizing denitrification processes through innovative technologies, modeling, and understanding microbial dynamics, wastewater treatment plants can effectively reduce nitrogen pollution and improve overall treatment efficiency. These efforts are essential for ensuring sustainable wastewater management practices that protect aquatic ecosystems and mitigate climate change impacts. The continued development and application of advanced denitrification strategies will be crucial for meeting the growing demands of wastewater treatment and environmental protection.

2.1.3   Stoichiometry of denitrification

The electron source of the denitrification process is organic matter, and the electron acceptor is NO_2 or NO_3. Denitrification reactions in which nitrate reduction is carried out with the help of wastewater and methanol are given in equations (2.23) and (2.24) (Metcalf & Eddy, 2003). $C_{10}H_{19}O_3N$ in equation (2.23) represents the organic matter in wastewater.

$$NO_3^- + 0.17C_{10}H_{19}O_3N + H^+$$
$$\longrightarrow 0.4N_2 + 0.15C_5H_7O_2N + 1.13H_2O + 0.91CO_2 \qquad (2.23)$$
$$+ 0.17NH_4^+ + 0.17OH^-$$

$$NO_3^- + 1.08CH_3OH + 0.073H_2CO_3$$
$$\longrightarrow 0.47N_2 + 0.056C_5H_7O_2N + 1.51H_2O + 0.83CO_2 \qquad (2.24)$$
$$+ OH^-$$
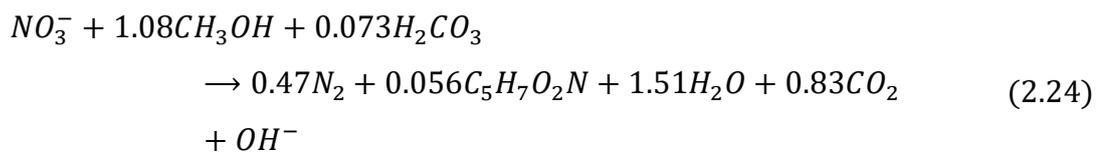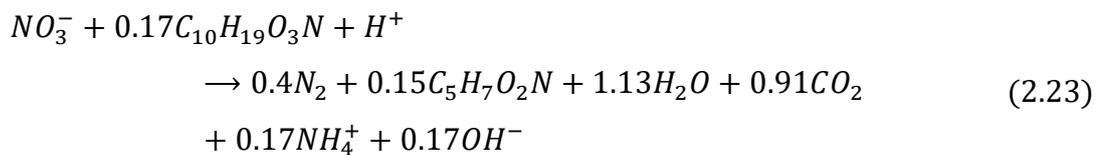
The production of alkalinity from the resulting hydroxyl (OH⁻) is shown in equation (2.25) (Metcalf & Eddy, 2003).

$$H_2CO_3 + 5CO_2 + 6OH^- \longrightarrow H_2O + 6HCO_3^-$$

(2.25)
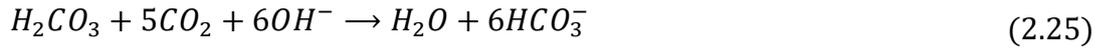
The general denitrification equation is given in equation (2.26) (Liu, 2018).

$$C_{10}H_{19}O_3N + 10NO_3^- \longrightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^-$$

(2.26)
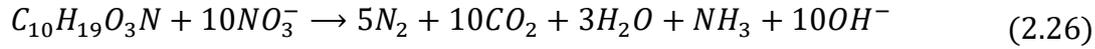
As can be seen from the above equations, alkalinity is produced in denitrification as opposed to nitrification. During the reduction of 1 g of nitrate, 3.57 g of alkalinity is produced. This amount is half of what is consumed in nitrification (Liu, 2018). If the alkalinity coming to the reactor with wastewater is not sufficient to neutralise the H+ ions in the environment, pH decreases, and nitrification is inhibited.

The effect of nitrification on pH in any wastewater can be determined. For example, if the wastewater has an alkalinity of 200 mg $CaCO_3$ and the expected nitrate production is 24 mgN/L, the expected alkalinity in the effluent is (200-7.14×24) = 29 mg/L $CaCO_3$. If half of the nitrate produced is denitrified, (0.5×24×3.57) = 43 mg/L $CaCO_3$ alkalinity is produced. In this case, the system will have (29+43) = 72 mg/L $CaCO_3$ alkalinity. Thus, the pH remains above 7. Generally, alkalinity above 40 mg/L is sufficient for pH to be above 7 (Henze et al., 2008).

The optimum conditions for the operation of the denitrification process are given in Table 2.1 (Liu, 2018).

Table 2.1. Optimum operating conditions for denitrication process.

Parameter	Unit	Value
Temperature	°C	20 – 40
Dissolved Oxygen	mg/L	<0.2
Free Nitrous Acid	mgN/L	<0.01
pH		7.0-7.5
Sludge Age	Day	3 – 6

2.1.4 Factors affecting nitrification and denitrification processes

Factors influencing nitrification and denitrification processes in wastewater treatment systems are determined by various environmental and operational parameters. These factors are crucial in regulating nitrogen removal efficiency. Dissolved oxygen levels significantly impact the efficiency of nitrification and denitrification processes. Low

dissolved oxygen concentrations can promote simultaneous nitrification and denitrification under anaerobic conditions, affecting nitrogen removal rates. Moreover, oxygen gradients within flocs can influence the transport of dissolved oxygen, further impacting nitrification and denitrification rates (Patoczka & Scheri, 2013; Sinha & Annachhatre, 2006; Lai et al., 2019). Denitrification processes can occur even at lower pH levels if dissolved oxygen concentrations are within the targeted range (Sinha & Annachhatre, 2006; Liu & Zhu, 2020; Mielcarek et al., 2021). Temperature is a key factor influencing the rates of nitrification and denitrification in wastewater treatment systems. Microbial activities responsible for nitrogen removal are temperature-dependent, with optimal temperature ranges supporting enhanced nitrification and denitrification rates. Higher temperatures can stimulate the activity of nitrifying and denitrifying bacteria, leading to increased nitrogen removal efficiency (Patoczka & Scheri, 2013; Yao et al., 2013; Lai et al., 2019). Organic carbon and nitrogen concentrations play a vital role in influencing the performance of denitrification processes in wastewater treatment plants. The availability of organic carbon and nitrogen sources directly impacts the efficiency of nitrogen removal processes. Storage and degradation of poly-beta-hydroxybutyrate (PHB) can provide essential carbon sources that benefit denitrification processes. Additionally, inhibiting nitrite oxidation can enhance denitrification rates, improving nitrogen removal efficiency and reducing organic matter requirements in wastewater treatment systems.

2.1.5   Nitrogen removal by different treatment configurations

Nitrogen removal in wastewater treatment can be achieved through various treatment configurations. Different studies have explored innovative approaches to enhance nitrogen removal efficiency. For instance, Scherson & Criddle (2014) discussed configurations involving complete hydrolysis of particulate bCOD, ammonification of organic nitrogen, and conventional nitrification-denitrification processes to remove total nitrogen. Wagner & Love (2022) found that a 2-stage configuration utilizing membrane aerated biofilm reactors resulted in a 20% higher nitrogen removal rate compared to other configurations. Moreover, Boas et al. (2018) highlighted nitrogen removal efficiencies ranging from 40% to 55% in constructed wetlands under different configurations. Fuente et al. (2022) emphasized the effectiveness of microbial electrochemical technologies in achieving high levels of carbon and nitrogen removal. Mai et al. (2021) discussed the shift towards more efficient processes like simultaneous

nitrification-denitrification and partial nitrification-anammox for nitrogen removal in industrial wastewater. Furthermore, Vela et al. (2015) pointed out that reactor configurations utilizing complex microbial metabolisms can achieve nitrogen removal while reducing energy consumption and greenhouse gas emissions. Paredes et al. (2007) highlighted various processes such as partial nitrification, anammox, and aerobic/anoxic deammonification, which have high potential for nitrogen removal. These studies collectively demonstrate the diverse strategies and technologies available for effective nitrogen removal in wastewater treatment.

2.1.5.1 A²O process

The A²O process, which stands for Anaerobic-Anoxic-Oxic, is a widely used configuration in wastewater treatment for efficient removal of nitrogen and phosphorus. This process involves three main stages: anaerobic, anoxic, and oxic. In the anaerobic stage, organic matter is broken down by anaerobic bacteria, producing substances that can be used by other bacteria in subsequent stages. The anoxic stage enables denitrification, during which nitrate is transformed into nitrogen gas in the absence of oxygen. Finally, in the oxic stage, aerobic bacteria convert ammonia to nitrate and then to nitrogen gas, completing the nitrogen removal process (Liu et al., 2008).
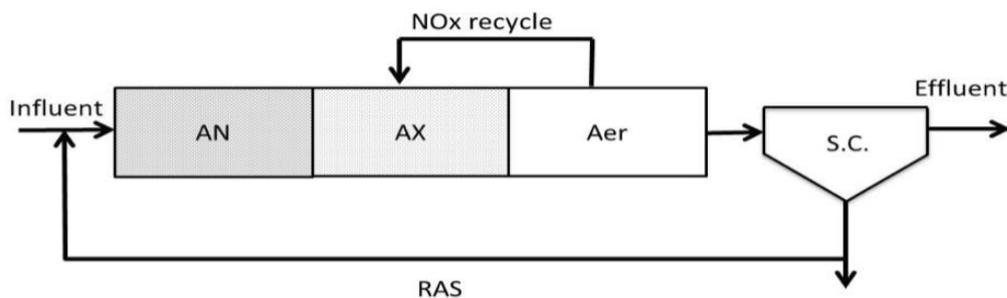
Figure 2.3. A²O process for nutrient removal (Metcalf & Eddy et al. (2014))[1].

The A²O process has been found to be highly effective in enhancing the biodegradability of wastewater through fermentation and achieving significant biological phosphorus removal. This process involves three distinct stages: an anaerobic stage where organic matter is fermented, an anoxic stage where denitrification occurs, and an oxic stage for nitrification. Each stage plays a crucial

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[1] AN= anaerobic, AX = anoxic, Aer = aerobic zone, S.C. = secondary clarifier.

role in the overall efficiency of the wastewater treatment process. The A^{2}O process can also be combined with other advanced treatment technologies, such as membrane bioreactors, to promote the growth of phosphorus-accumulating organisms (PAOs), further improving phosphorus removal efficiency (Li et al., 2016). By integrating membrane bioreactors, the A^{2}O process benefits from the enhanced separation of biomass and treated effluent, leading to higher quality discharge and improved process stability. The A^{2}O process has been extensively studied in the context of pharmaceutical removal in sewage treatment plants, showing promising results in the removal of various pharmaceutical compounds (Park et al., 2020). Pharmaceuticals are often present in trace amounts in wastewater and can have detrimental effects on aquatic life and human health if not adequately removed. The A^{2}O process's ability to degrade complex organic molecules makes it particularly effective in this regard, ensuring that treated effluent meets stringent environmental standards. Moreover, the A^{2}O process has been applied in various industrial settings, such as textile dyeing wastewater treatment, where it demonstrated superior efficiency in Chemical Oxygen Demand (COD) removal compared to other systems (Park et al., 2010). Textile dyeing wastewater is characterized by high concentrations of organic pollutants and color, making it challenging to treat. The A^{2}O process's multi-stage design allows for the effective breakdown and removal of these pollutants, resulting in clearer and cleaner effluent. Studies have also evaluated the impact of nitrite accumulation on phosphorus removal within the A^{2}O process, highlighting its importance in achieving high nitrogen and phosphorus removal in sewage treatment (Zeng et al., 2011). Nitrite accumulation can inhibit biological phosphorus removal, but the controlled conditions within the A^{2}O process help mitigate this issue, ensuring efficient nutrient removal. Furthermore, the A^{2}O process has been integrated with technologies like iron-carbon galvanic cells to enhance its performance in treating high-nitrogen/phosphorus and low-carbon sewage (Peng et al., 2020). Iron-carbon galvanic cells generate iron ions and electrons that can aid in the removal of pollutants, complementing the biological processes in the A^{2}O system and improving overall treatment efficiency. The versatility of the A^{2}O process extends to its adaptability in various wastewater treatment scenarios. Its multi-stage design not only facilitates efficient organic matter degradation and nutrient removal but also allows for flexibility in operation and integration with other treatment technologies. This adaptability makes the A^{2}O process

a valuable tool in sustainable wastewater treatment practices, capable of meeting diverse treatment needs and regulatory requirements.

The A^{2}O process is a versatile and effective configuration for wastewater treatment, particularly in the removal of nitrogen and phosphorus. Its multi-stage design allows for efficient organic matter degradation, denitrification, and phosphorus removal, making it a valuable tool in sustainable wastewater treatment practices. By combining biological processes with advanced treatment technologies, the A^{2}O process offers a robust solution for treating a wide range of wastewater types, ensuring high effluent quality and compliance with environmental standards. The continued development and optimization of the A^{2}O process will play a crucial role in addressing the growing challenges of wastewater treatment and environmental protection.

2.1.5.2 Five-stage Bardenpho process

The five-stage Bardenpho process is a sophisticated wastewater treatment configuration specifically designed to efficiently remove nitrogen and phosphorus from sewage, addressing both environmental and regulatory challenges. This process is structured around five distinct compartments: anaerobic, anoxic, oxic, anoxic, and oxic. Each of these compartments serves a unique and critical function in the overall nutrient removal process, ensuring the effective treatment of wastewater. In the anaerobic compartment, the initial stage, organic matter is broken down by anaerobic bacteria in the absence of oxygen. This stage is crucial for the release of phosphorus from polyphosphate-accumulating organisms (PAOs), setting the stage for subsequent biological phosphorus removal. The breakdown of organic matter under anaerobic conditions produces volatile fatty acids (VFAs), which are essential for the next stages of treatment. Following the anaerobic compartment is the first anoxic compartment, where denitrification occurs. In this phase, denitrifying bacteria convert nitrate to nitrogen gas when oxygen is absent. This process is vital for the removal of nitrogen from the wastewater, as it converts bioavailable nitrogen compounds into inert nitrogen gas, which is then released into the atmosphere. The presence of VFAs from the anaerobic stage aids in providing the necessary carbon source for denitrification, enhancing the efficiency of nitrogen removal. The subsequent oxic compartment is where nitrification takes place. In this aerobic environment, ammonia-oxidizing bacteria (AOB) convert ammonia to nitrite, and nitrite-oxidizing bacteria (NOB)

further convert nitrite to nitrate. This step is crucial for transforming ammonia, a toxic compound to aquatic life, into nitrate, which can be further treated in the following anoxic stage. The second anoxic compartment follows, where additional denitrification occurs. This stage ensures that any remaining nitrate produced in the previous oxic stage is reduced to nitrogen gas. By having two anoxic stages, the five-stage Bardenpho process significantly enhances the overall denitrification efficiency, ensuring that minimal nitrogen remains in the treated effluent. The process concludes with the second oxic compartment. In this final stage, any residual organic matter and ammonia are oxidized, ensuring that the effluent meets stringent discharge standards. This stage also helps in the polishing of the treated water, ensuring that it is of high quality before being discharged into natural water bodies or reused. The primary goal of the five-stage Bardenpho process is to reduce nitrogen loads by enhancing denitrification processes within the anoxic compartments (Schmitz et al., 2016). This process configuration is designed to maximize nitrogen and phosphorus removal while maintaining operational efficiency. The sequential arrangement of anaerobic, anoxic, and oxic compartments creates an environment where biological nutrient removal processes can occur optimally. Furthermore, the five-stage Bardenpho process has been shown to improve overall treatment performance by providing multiple opportunities for nutrient removal. The repeated cycling between anoxic and oxic conditions allows for the thorough removal of nitrogen compounds, reducing the risk of eutrophication in receiving water bodies. Additionally, the anaerobic stage enhances phosphorus removal by facilitating the uptake and storage of phosphorus by PAOs, which is later removed as part of the sludge. Research has demonstrated that the five-stage Bardenpho process significantly improves the efficiency of denitrification and biological phosphorus removal, thereby enhancing overall nutrient removal efficiency (Schmitz et al., 2016).
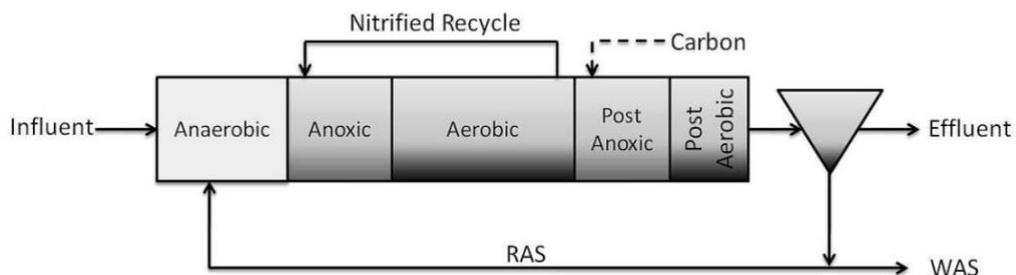
Figure 2.4. Process configuration – five-stage Bardenpho process.

By optimizing conditions for biological nutrient removal (BNR) through these sequential zones, the process effectively eliminates nitrogen and phosphorus species from wastewater. Studies have demonstrated that the five-stage Bardenpho process significantly improves denitrification and biological phosphorus removal, thereby enhancing overall nutrient removal efficiency (Schmitz et al., 2016). The process design allows for internal recycling of nitrate, preventing nitrate recycling issues into the anaerobic zone and further optimizing nutrient removal. Moreover, integrating the process with membrane bioreactors enhances phosphorus removal efficiency by promoting the growth of phosphorus-accumulating organisms, thereby improving overall nutrient removal performance (Schmitz et al., 2016). Research has also investigated the impact of distributed state effects on enhanced biological phosphorus removal within the five-stage Bardenpho process. By modeling individual bacteria to consider their hydraulic experiences, researchers have explored how internal recycle flows in this process influence distributed state development, offering insights into optimizing phosphorus removal (Schuler & Xiao, 2008). Additionally, evaluations have shown that the process emits fewer greenhouse gases compared to other treatment configurations, underscoring its environmental sustainability. In summary, the five-stage Bardenpho process is a sophisticated and effective wastewater treatment configuration that achieves high levels of nitrogen and phosphorus removal. Through a series of compartments with specific functions and the integration of advanced technologies, this process plays a crucial role in sustainable wastewater treatment practices.

2.1.5.3 Johannesburg (JHB) process

The Johannesburg (JHB) process is a wastewater treatment configuration that plays a critical role in biological nutrient removal (BNR) processes, specifically targeting the elimination of nitrogen and phosphorus from sewage. This process is meticulously designed with multiple stages, each optimized to maximize nutrient removal efficiency. The JHB process is renowned for its effectiveness in managing varying sewage strengths and compositions, making it a versatile and robust solution for wastewater treatment. A comprehensive study assessing the JHB process's effectiveness in biological phosphorus (bio-P) removal over a two-year period highlighted its adaptability and efficiency in handling different sewage strengths (Li et al., 2017). This long-term study demonstrated that the JHB process consistently

achieved high levels of phosphorus removal, even when the influent sewage characteristics varied significantly. Such adaptability is crucial for wastewater treatment plants that deal with fluctuating inflow conditions, ensuring stable and reliable operation under diverse scenarios. The JHB process is often compared to other advanced treatment configurations, such as the five-stage Bardenpho process, to analyze the influence of sewage characteristics on nutrient removal efficiency (Manyumba et al., 2009). These comparative studies are crucial for determining the advantages and disadvantages of various treatment technologies, aiding in the selection of the most suitable process for specific wastewater treatment requirements. The JHB process involves a sequence of anaerobic, anoxic, and aerobic stages, each contributing to the overall nutrient removal. In the anaerobic stage, organic matter is broken down by anaerobic bacteria, releasing phosphorus into the liquid phase. This release is a precursor for subsequent phosphorus uptake by polyphosphate-accumulating organisms (PAOs) in the aerobic stage. The anoxic stages facilitate denitrification, where nitrate is reduced to nitrogen gas, effectively removing nitrogen from the wastewater. One of the distinctive features of the JHB process is its flexibility in managing the return activated sludge (RAS) flow. The JHB process, therefore, not only enhances the efficiency of nutrient removal but also provides operational adaptability, making it a robust and reliable option for wastewater treatment facilities. This adaptability is particularly important in dealing with fluctuating influent characteristics and varying environmental conditions, ensuring consistent treatment performance and compliance with environmental regulations. The integration of advanced process control strategies further augments the effectiveness of the JHB process, enabling precise management of biological nutrient removal and contributing to sustainable wastewater management practices. The process allows for the RAS to be recirculated to the anoxic stage, enhancing denitrification and reducing nitrate levels before the flow reaches the aerobic stage. This internal recycling is critical for optimizing nitrogen removal and preventing the backflow of nitrates into the anaerobic zone, which could otherwise inhibit phosphorus release and uptake processes. Research has also focused on the population dynamics of nitrifying and denitrifying bacteria within the JHB process, demonstrating its capability to achieve efficient nitritation, with high nitrite accumulation ratios (Zeng et al., 2014). This ability to promote partial nitrification is beneficial for subsequent denitrification stages, as it simplifies the reduction process and reduces the overall oxygen demand, thereby

saving energy and operational costs. Further studies have explored the application of the JHB process in treating high-strength industrial wastewater, such as that from dairy processing facilities. These studies have shown that the JHB process can effectively handle high organic loads and complex waste streams, maintaining high nutrient removal efficiencies and stable operation (Erkan et al., 2018). The robustness of the JHB process in such challenging conditions underscores its versatility and effectiveness as a BNR strategy.
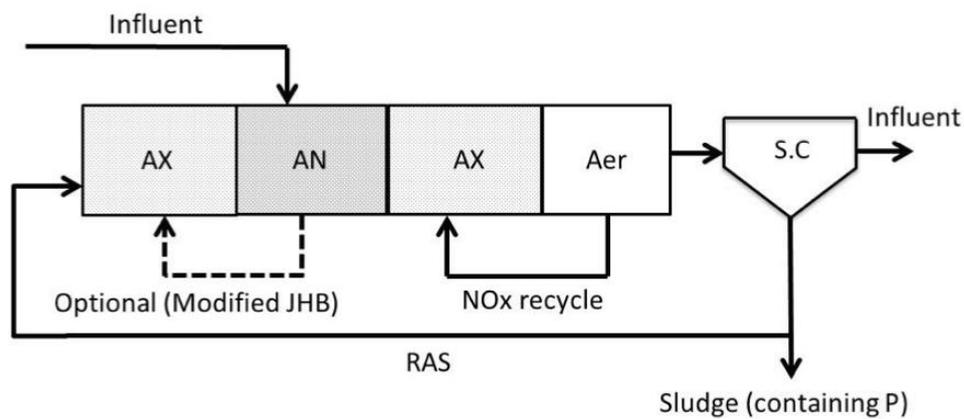
Figure 2.5. Johannesburg (JHB) process diagram (Metcalf & Eddy et al. (2014))[2].

In the Johannesburg (JHB) process, the mixed liquor from the aerobic zone flows past the settler, while the return sludge is channeled to the anoxic zone to promote denitrification and phosphorus removal (Kuzminskiy et al., 2019). This process configuration belongs to a lineage of South African wastewater treatment concepts, which also includes the University of Cape Town (UCT) process and the modified University of Cape Town (MUCT) process (Mąkinia, 2010). The JHB process has been extensively studied for its ability to achieve nitritation, characterized by high nitrite accumulation ratios, which indicates efficient nitrogen removal (Zeng et al., 2014). This high efficiency in nitrogen removal makes the JHB process a valuable method in wastewater treatment, contributing to improved water quality and compliance with stringent environmental regulations. The advancements in this process underline its significance in the evolution of wastewater treatment technologies, particularly in its effectiveness in handling nitrogen and phosphorus, two critical pollutants in wastewater management.

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[2] AN= anaerobic, AX = anoxic, Aer = aerobic zone, S.C. = secondary clarifier.

A conceptual diagram of UCT/VIP process is shown in Figure 2.6.
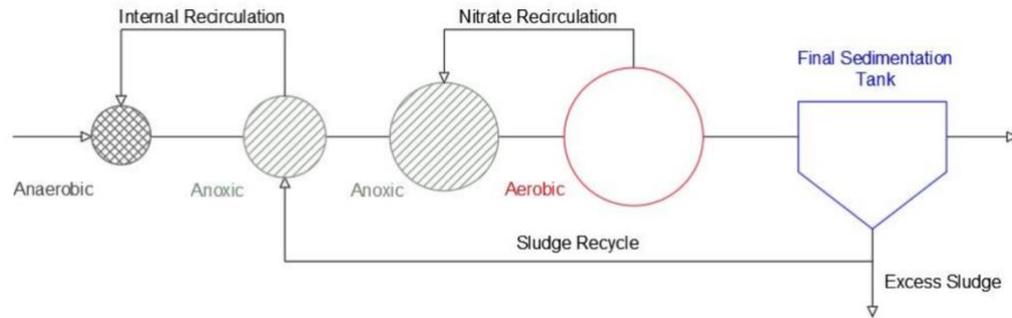
Figure 2.6. UCT/VIP process.

Furthermore, research has delved into the population dynamics of nitrifying bacteria in the JHB process, demonstrating its role in achieving nitritation in municipal wastewater treatment (Zeng et al., 2014). This process has also been explored in the treatment of high-strength dairy wastewater, showcasing its versatility in addressing various wastewater challenges (Erkan et al., 2018). Additionally, the JHB process has been associated with the removal of organic matter and nutrients, underscoring its significance in sustainable wastewater treatment practices (Kuzminskiy et al., 2019). In summary, the Johannesburg (JHB) process is a significant wastewater treatment configuration recognized for its efficacy in biological nutrient removal, particularly in nitrogen and phosphorus removal. Through its distinctive design and operational strategies, the JHB process contributes to the efficient treatment of sewage and the preservation of water resources.

2.2 Biological Phosphorus Removal

Biological phosphorus removal is a critical process in wastewater treatment aimed at preventing the eutrophication of water bodies, which can lead to harmful algal blooms and deteriorated water quality. Enhanced biological phosphorus removal (EBPR) is a commonly used method involving the uptake of phosphorus by specific microorganisms during the treatment process (Zhang et al., 2013). This process is typically achieved through the activity of polyphosphate-accumulating organisms (PAOs) under alternating anaerobic-aerobic conditions (Zeng et al., 2003). In the EBPR process, wastewater first enters an anaerobic zone where PAOs release stored polyphosphate and uptake volatile fatty acids (VFAs), storing them as

polyhydroxyalkanoates (PHAs). This anaerobic release of phosphorus is a preparatory step for subsequent aerobic uptake. When the wastewater moves into the aerobic zone, PAOs use the stored PHAs for growth and energy, taking up phosphorus from the wastewater and storing it as intracellular polyphosphate granules. Successful EBPR leads to a net removal of phosphorus, where the amount of phosphorus taken up aerobically exceeds the amount released anaerobically (Zheng et al., 2011). In wastewater treatment plants, identifying and characterizing the specific organisms involved in phosphate uptake, such as Rhodocyclus-related organisms, has been challenging despite the successful application of EBPR at full scale (Zilles et al., 2002). These PAOs play a crucial role in the efficiency of EBPR systems, but their identification and monitoring remain complex due to the diverse microbial communities present in treatment systems. Nitrate accumulation has been recognized as a hindrance to stable and reliable EBPR processes (Yılmaz et al., 2007). Nitrate can compete with phosphorus for uptake sites in PAOs and inhibit their activity. To overcome this challenge, denitrifying phosphorus removal technologies have been developed. These technologies enable simultaneous denitrification and phosphorus removal, where PAOs can use nitrate as an electron acceptor under anoxic conditions, facilitating phosphorus uptake even in the presence of nitrate (Sun & Zheng, 2015). While biological processes are effective in phosphorus removal, they may not achieve complete removal, with only a fraction of phosphorus compounds being eliminated (Hernandez et al., 2006). To enhance phosphorus removal efficiency, various strategies have been explored. For example, the addition of chitosan, a natural polymer, has shown improved total phosphorus removal from wastewater by enhancing the flocculation and settling of phosphorus-containing particles (Zhao et al., 2021). Moreover, phosphorus recovery technologies, such as struvite crystallization, have been recommended for treating sludge digester liquors in wastewater treatment plants with EBPR (Martí et al., 2010). Struvite, a mineral composed of magnesium, ammonium, and phosphate, can be precipitated and recovered from wastewater, providing a valuable resource for fertilizer production and reducing the phosphorus load in the effluent.

Figure 2.7 provides a schematic representation of the process in anaerobic reactors. In these reactors, PAOs release phosphorus and uptake VFAs, storing them as PHAs. Subsequently, in the aerobic (or anoxic) reactor depicted in Figure 2.8, PAOs utilize the stored PHAs to transform orthophosphates into polyphosphates, which are then

incorporated into their cellular structure. This transformation facilitates the reduction of phosphorus levels in wastewater through sludge removal, achieving the desired effluent concentration. In aerobic and anoxic zones, oxygen and nitrate serve as electron acceptors, respectively, whereas in the anaerobic zone, the synthesis of PHAs requires a source of reducing power (Seviour et al., 2003). This interplay of different environmental conditions ensures the effective cycling of phosphorus within the microbial community, optimizing phosphorus removal from wastewater.

EBPR is a vital process in wastewater treatment for preventing eutrophication and maintaining water quality. The success of EBPR relies on the activity of polyphosphate-accumulating organisms (PAOs) and the careful management of anaerobic, aerobic, and anoxic conditions. Despite challenges such as nitrate accumulation, advancements in denitrifying phosphorus removal technologies and the integration of recovery methods like struvite crystallization have significantly improved phosphorus removal efficiency. Continued research and innovation in this field are essential for developing sustainable and effective wastewater treatment solutions that protect our water resources and promote environmental health.
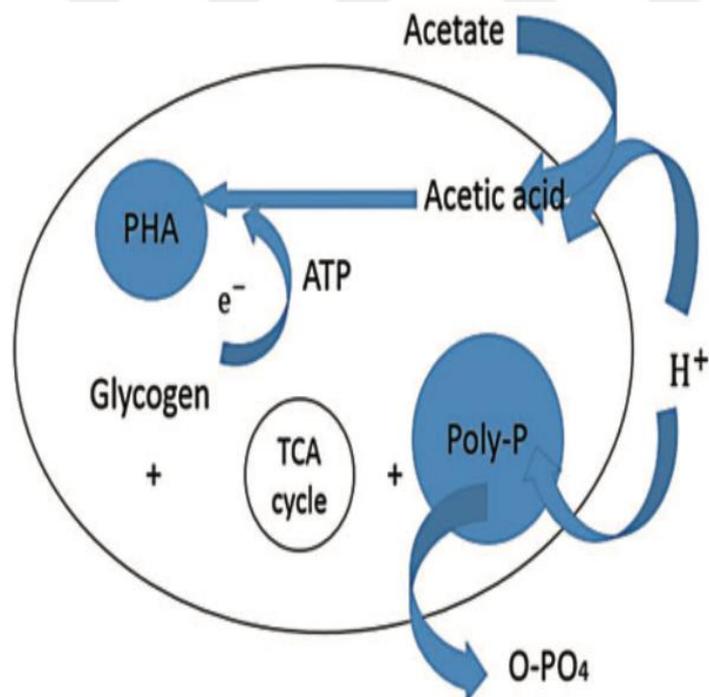
Figure 2.7. Biological phosphorus removal microbiology – anaerobic zone (Seviour et al. 2003).
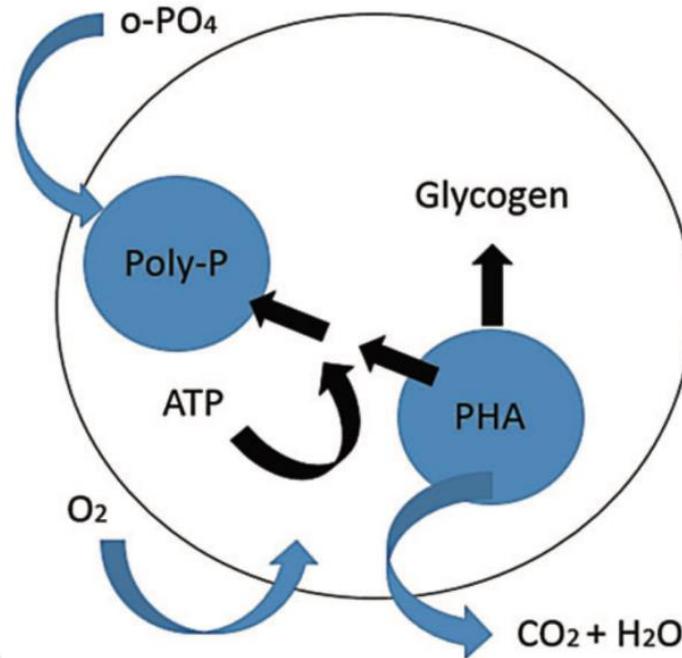
Figure 2.8. Biological phosphorus removal microbiology – aerobic zone (Seviour et al. 2003).

2.2.1 Importance of phosphorus removal

Phosphorus removal from wastewater is crucial for environmental protection, particularly to mitigate eutrophication in receiving waters. The presence of phosphorus in domestic wastewater poses a significant risk of eutrophication, making its removal a common practice mandated in many countries (Bunce et al., 2018). Eutrophication leads to excessive growth of algae and aquatic plants, which can result in oxygen depletion, harming aquatic ecosystems, and leading to the death of fish and other marine life. The recirculation of nitrate to the anaerobic tank can have significant adverse effects on biological phosphorus removal processes. To examine this impact in more detail, it is necessary to focus on the effect of nitrate entering the anaerobic tank on the volatile fatty acids (VFAs) Chemical Oxygen Demand (COD). Research indicates that each gram of nitrate entering the anaerobic tank reduces approximately 5 grams of VFA COD. This information is critical for understanding the efficiency of phosphorus removal processes. In practice, approximately 10 grams of VFA COD are required to remove 1 gram of phosphorus in biological phosphorus removal. This ratio represents the amount of energy needed for the metabolic activities of polyphosphate-accumulating organisms (PAOs). PAOs use VFAs as an energy source while storing phosphorus within their cells. Therefore, nitrate entering the anaerobic tank reduces the availability of VFAs for phosphorus removal.

In the case of nitrate recirculation to the anaerobic tank, approximately 0.5 mgP/L of phosphorus removal potential is lost for every gram of nitrate nitrogen. This loss decreases the efficiency of phosphorus removal processes and negatively impacts the overall performance of the treatment plant. Nitrate recirculation disrupts anaerobic conditions, limiting the ability of PAOs to release phosphorus. PAOs release phosphorus under anaerobic conditions and take it up again under aerobic conditions. The recirculation of nitrate to the anaerobic environment reduces the VFAs necessary for PAOs to re-uptake released phosphorus.

During nitrification and denitrification processes, NH_4^+ is oxidized to NO_2^- and then to NO_3^- during nitrification. In the denitrification process, nitrate is reduced to N_2 under anoxic (oxygen-free) conditions. However, the recirculation of nitrate to the anaerobic tank disrupts these anoxic conditions, negatively affecting these processes. Nitrate interferes with the process where PAOs need to release phosphorus under anaerobic conditions.

The recirculation of nitrate to the anaerobic tank is a critical issue that must be carefully managed in biological phosphorus removal processes. Maintaining anaerobic conditions and appropriately regulating nitrification-denitrification processes are essential for optimal phosphorus removal. These adjustments are crucial for enhancing the efficiency of the treatment plant and ensuring compliance with environmental regulations. Careful monitoring of recirculation rates and conditions can enhance the efficiency of biological phosphorus removal and overall treatment processes. Additionally, implementing advanced control strategies to optimize these processes' energy and operational costs is important. Such strategies can be seen as significant steps towards improving the plant's long-term sustainability and environmental performance. Also, in wastewater treatment systems, maintaining specific DO concentrations is essential for biological phosphorus removal. The presence of adequate DO levels ensures that aerobic conditions are maintained, which is necessary for the effective functioning of phosphorus-accumulating organisms (PAOs). These organisms play a key role in the enhanced biological phosphorus removal (EBPR) process by taking up and storing phosphorus under aerobic conditions. Thus, the removal of phosphorus is crucial for maintaining the health and balance of aquatic environments. Enhanced Biological Phosphorus Removal (EBPR) is a key process employed in wastewater treatment plants to recover substantial quantities of phosphorus from wastewater (Coats et al., 2021). EBPR processes leverage the activity

of polyphosphate-accumulating organisms (PAOs), which take up and store phosphorus within their cells under alternating anaerobic and aerobic conditions. These organisms play a pivotal role in the EBPR process by facilitating the removal and recovery of phosphorus during the wastewater treatment cycle (Barr et al., 2010). The widespread use of EBPR for carbon and phosphorus removal highlights its effectiveness in achieving low phosphorus concentrations in treated effluent, thereby preventing eutrophication in natural water bodies. One such method involves the use of steel slag as a filter system, which has shown promising results in removing phosphate from wastewater (Ahmad et al., 2020). Steel slag, a byproduct of the steel manufacturing process, is effective due to its high calcium content, which reacts with phosphate to form insoluble calcium phosphate compounds that can be easily removed from the water. This approach not only enhances phosphorus removal but also provides a valuable use for industrial byproducts, contributing to a circular economy. Another innovative method for phosphorus removal is the application of hydrated lime. Hydrated lime has been found to be effective in killing pathogens and extracting phosphorus from manure, making it an attractive option for wastewater treatment (Viancelli et al., 2015). When added to wastewater, hydrated lime raises the pH, leading to the precipitation of phosphorus as calcium phosphate. This method not only aids in phosphorus removal but also helps in disinfecting the wastewater, thus addressing multiple treatment objectives simultaneously. Advanced biological approaches are continuously being explored to optimize phosphorus removal. The integration of biofilm reactors, where microorganisms grow on surfaces, with traditional activated sludge systems, can enhance the efficiency of phosphorus uptake by providing additional surface area and retention time for PAOs. This integration can lead to more stable and robust EBPR processes, capable of handling variable wastewater loads and compositions. The recovery of phosphorus from wastewater is increasingly recognized as an essential aspect of sustainable resource management. By optimizing process design, operation, and control strategies, wastewater treatment facilities can effectively manage nitrate levels, enhance phosphorus removal efficiency, and ensure the sustainability and cost-effectiveness of the treatment process. Technologies such as struvite crystallization enable the recovery of phosphorus in a form that can be reused as fertilizer. Struvite (magnesium ammonium phosphate) precipitation from wastewater streams, especially in sludge digesters, not

only reduces the phosphorus load in the effluent but also provides a valuable nutrient source for agricultural applications (Martí et al., 2010).

The implementation of these diverse technologies and methods is critical for addressing the complex challenge of phosphorus removal in wastewater treatment. Effective phosphorus removal not only protects water quality and preserves aquatic ecosystems but also supports the sustainable management of nutrient resources. As environmental regulations become more stringent, the need for innovative and efficient phosphorus removal technologies will continue to grow. The importance of phosphorus removal from wastewater cannot be overstated, as it plays a vital role in protecting water quality and preserving aquatic ecosystems. It plays a fundamental role in protecting aquatic ecosystems, ensuring compliance with environmental regulations, and supporting broader sustainability objectives. By implementing and optimizing phosphorus removal processes, wastewater treatment facilities can significantly contribute to the preservation of water quality and the health of aquatic environments. The adoption of Enhanced Biological Phosphorus Removal (EBPR) processes, along with innovative filtration systems such as steel slag filters and hydrated lime treatment, is essential for achieving sustainable wastewater management. Additionally, the recovery and reuse of phosphorus through technologies like struvite crystallization contribute to a circular economy and resource conservation. By implementing these effective phosphorus removal strategies, wastewater treatment plants can significantly reduce the environmental impact of phosphorus discharges and support the long-term health of aquatic environments.

2.2.2   Advantages & Disadvantages of biological phosphorus removal process

Biological phosphorus removal processes, such as EBPR, offer several advantages and disadvantages in wastewater treatment. While EBPR offers significant environmental and economic benefits, its successful implementation requires careful management and an understanding of the complex interactions within the biological system. The process's sensitivity to operational conditions and external factors highlights the need for robust monitoring and control strategies to ensure consistent and reliable phosphorus removal.

Table 2.2. Advantages of biological phosphorus removal process.

Advantages	Explanation
Environmentally Friendly	Biological phosphorus removal processes are environmentally friendly as they do not rely on chemical additives, reducing the use of harsh chemicals in wastewater treatment (Seviour et al. (2003)).
Cost-Effective	Compared to chemical phosphorus removal methods, biological processes are often more cost-effective, making them a sustainable option for wastewater treatment (Rashed & Massoud, 2015).
Efficient Nutrient Removal	EBPR processes efficiently remove phosphorus from wastewater, contributing to the protection of water bodies from eutrophication (Barr et al., 2010).
Reduced Chemical Dependency	By utilizing microbial activities, biological phosphorus removal processes reduce the dependency on chemical additives, promoting a more natural treatment approach (Hu et al., 2018).

Table 2.3. Disadvantages of biological phosphorus removal process.

Disadvantages	Explanation
Long Retention Time	Biological phosphorus removal processes may require longer retention times compared to chemical methods, potentially impacting the overall treatment efficiency (Ananthashankar, 2013).
Sensitivity to Toxic Metals	Presence of toxic metals in wastewater can hinder the growth of microorganisms involved in phosphorus removal, affecting process efficiency (Ananthashankar, 2013).
Limited Efficiency	Biological phosphorus removal processes may not achieve complete phosphorus removal, leading to residual phosphorus in the effluent, which can still pose risks to receiving waters (Li et al., 2011).

While biological phosphorus removal processes offer several advantages such as environmental sustainability and cost-effectiveness, they also come with challenges related to process control, efficiency, and sensitivity to environmental factors. Understanding these advantages and disadvantages is crucial for optimizing the performance of biological phosphorus removal in wastewater treatment.

2.3 Carousel Reactors

Carousel reactors represent an advanced form of the activated sludge process that is widely employed in the biological treatment of wastewater, particularly for the

removal of nitrogen. These systems are designed to provide an efficient and cost-effective solution for the treatment of municipal and industrial wastewater, with the added capability of removing organic pollutants, nitrogen, and phosphorus. The versatility and effectiveness of carousel reactors make them an essential component in modern wastewater treatment facilities. The design of carousel reactors is characterized by their oval or circular shape, which creates a continuous racetrack-like flow pattern. This unique configuration allows for the establishment of distinct zones within the reactor, each tailored to facilitate specific biological processes. The continuous flow of wastewater and activated sludge around the reactor ensures that the biomass remains in constant contact with the incoming wastewater, promoting efficient treatment. The racetrack configuration enhances mixing and prevents short-circuiting, ensuring uniform distribution of nutrients and oxygen throughout the reactor. One of the key features of carousel reactors is their ability to support both aerobic and anoxic processes within the same system. Aerobic zones are equipped with mechanical aerators or fine bubble diffusers that supply oxygen to the mixed liquor, enabling the aerobic microorganisms to break down organic matter and convert ammonia to nitrate through the process of nitrification. This stage is crucial for the initial breakdown of organic pollutants and the conversion of ammonia, a toxic compound, into nitrate, which can be further treated in the subsequent anoxic zones. In contrast, anoxic zones are designed to create oxygen-depleted conditions, where denitrifying bacteria can thrive and reduce nitrate to nitrogen gas, thereby achieving nitrogen removal. The anoxic zones are strategically placed to maximize the contact time between nitrate and denitrifying bacteria, ensuring efficient nitrogen removal. The transition between aerobic and anoxic conditions within the carousel reactor allows for simultaneous nitrification and denitrification, optimizing the overall nitrogen removal process. The flexibility of carousel reactors extends to phosphorus removal, which is achieved through the process of enhanced biological phosphorus removal (EBPR). In this process, specific groups of bacteria, known as polyphosphate-accumulating organisms (PAOs), are encouraged to uptake and store phosphorus under alternating aerobic and anaerobic conditions. During the anaerobic phase, PAOs release phosphorus into the liquid phase, which is then taken up and stored as polyphosphate granules during the aerobic phase. The sludge containing these bacteria is then removed from the system, effectively reducing the phosphorus content in the treated effluent. This cyclical process ensures that phosphorus levels in the effluent are

minimized, meeting stringent environmental standards. The design and operational flexibility of carousel reactors make them suitable for a wide range of applications. They can handle varying wastewater loads and compositions, making them ideal for both municipal and industrial wastewater treatment. The ability to easily adjust aeration rates and flow patterns allows operators to optimize the reactor's performance based on the specific characteristics of the incoming wastewater. Furthermore, the integration of advanced monitoring and control systems in carousel reactors enhances their efficiency and reliability. Real-time monitoring of dissolved oxygen levels, oxidation-reduction potential (ORP), and nutrient concentrations allows for precise control of the treatment process. Automated control systems can adjust aeration and mixing rates in response to changing conditions, ensuring consistent treatment performance and energy efficiency. In addition to their technical advantages, carousel reactors offer economic benefits. Their efficient design reduces the footprint of the treatment facility, saving on construction and operational costs. The ability to achieve high removal efficiencies for nitrogen, phosphorus, and organic pollutants translates to lower costs for chemical additives and sludge disposal. The application of carousel reactors in wastewater treatment has been extensively documented and validated in various studies. For instance, Metcalf & Eddy (2003) highlighted the effectiveness of carousel reactors in achieving stringent effluent quality standards while maintaining operational simplicity and robustness. These reactors have been successfully implemented in numerous wastewater treatment plants worldwide, demonstrating their scalability and adaptability to different environmental and regulatory contexts. Carousel reactors represent a state-of-the-art solution for the biological treatment of wastewater, offering a robust and flexible approach to removing nitrogen, phosphorus, and organic pollutants. By implementing carousel reactors, wastewater treatment plants can effectively meet regulatory requirements. Their advanced design, combining aerobic and anoxic processes within a single system, ensures high treatment efficiency and operational reliability. By incorporating enhanced biological phosphorus removal and advanced control systems, carousel reactors meet the demands of modern wastewater treatment, providing sustainable and cost-effective solutions for protecting water quality and public health. The continued development and optimization of carousel reactor technology will play a vital role in addressing the evolving challenges of wastewater management and environmental protection (Metcalf & Eddy, 2003).

2.3.1 Nitrogen and phosphorus removal in carousel reactors

Nitrogen and phosphorus removal in carousel reactors is an advanced and essential process within modern wastewater treatment facilities, addressing critical environmental concerns and regulatory requirements. Carousel reactors, with their unique continuous flow and aerated design, facilitate the efficient removal of nitrogen and phosphorus through a series of carefully controlled biological processes. These reactors are engineered to create alternating aerobic and anoxic zones, which are crucial for the sequential steps of nitrification and denitrification required for effective nitrogen removal. During nitrification, autotrophic bacteria oxidize ammonia to nitrate in the aerobic zones. This conversion is a two-step process where ammonia-oxidizing bacteria (AOB) first convert ammonia to nitrite, followed by nitrite-oxidizing bacteria (NOB) converting nitrite to nitrate. The nitrate produced is then subjected to denitrification in the anoxic zones, where heterotrophic bacteria utilize it as an electron acceptor, reducing it to nitrogen gas that is released harmlessly into the atmosphere. This reduction is facilitated by the presence of readily biodegradable organic matter, which serves as the carbon source for the denitrifying bacteria. The cyclical operation of the carousel reactor, with its controlled aeration and mixing, ensures that the conditions for these processes are consistently maintained, enhancing nitrogen removal efficiency. Phosphorus removal is achieved through the EBPR process. In this process, specific bacteria known as polyphosphate-accumulating organisms (PAOs) play a pivotal role. Under anaerobic conditions, PAOs uptake volatile fatty acids (VFAs) and store them as polyhydroxyalkanoates (PHAs), releasing phosphate into the water. When the conditions shift to aerobic, PAOs utilize the stored PHAs for growth and energy, taking up more phosphate than they released anaerobically and storing it intracellularly as polyphosphate granules. This results in a net removal of phosphorus from the wastewater. The precise control of the dissolved oxygen set-points and the strategic design of anaerobic, anoxic, and aerobic zones within the carousel reactors are essential for optimizing the EBPR process. The integration of these biological processes in carousel reactors not only ensures high removal efficiencies for nitrogen and phosphorus but also contributes to the overall sustainability and cost-effectiveness of wastewater treatment operations. By reducing the levels of these nutrients in the effluent, treatment plants can prevent eutrophication in receiving water bodies, which is essential for maintaining aquatic ecosystems. The

operational strategies employed in carousel reactors are supported by extensive research and case studies, including those by Henze et al. (2008) and Metcalf & Eddy (2014), which provide detailed insights into the optimization and performance of these systems.

2.3.2 Oxygen distribution in carousel systems

Carousel systems are a sophisticated type of activated sludge process used in wastewater treatment plants. These systems are meticulously designed to provide efficient biological treatment of wastewater by promoting the growth of aerobic microorganisms. Oxygen distribution plays a critical role in the performance of carousel systems, as it directly impacts the biological processes involved in the treatment of wastewater. In carousel systems, oxygen is essential for the aerobic microorganisms that degrade organic pollutants present in the wastewater. These microorganisms require oxygen to break down organic matter through aerobic respiration, converting it into carbon dioxide, water, and biomass. The efficiency of this biological treatment process is highly dependent on the availability of dissolved oxygen in the system (Rosso et al., 2008). The distribution of oxygen in carousel systems is achieved through a carefully planned aeration process. Aeration involves the introduction of air into the wastewater, typically done using mechanical aerators or diffusers. In carousel systems, the aeration equipment is strategically placed to create a circular flow pattern, which helps in the uniform distribution of oxygen throughout the treatment tank. This strategic placement ensures that the entire volume of the reactor receives adequate oxygen, thus supporting the aerobic processes necessary for effective wastewater treatment. The circular flow pattern in carousel systems is instrumental in maintaining optimal contact between the wastewater and the microorganisms. This flow pattern ensures that the microorganisms are continuously exposed to fresh supplies of oxygen, which is crucial for their metabolic activities. Additionally, the circular flow helps in preventing the settling of solids, thereby maintaining a homogeneous mixture of activated sludge and wastewater. This constant mixing not only aids in maintaining the efficiency of the biological processes but also helps in avoiding the formation of anaerobic zones that could hinder the treatment process.

The distribution of oxygen in carousel systems is a critical aspect of wastewater treatment, as it directly impacts the efficiency of the biological processes involved.

Several factors influence the distribution of oxygen in these systems, each playing a crucial role in ensuring optimal conditions for the treatment process. These factors include (Drewnowski et al., 2019):

- *Aeration Rate:* The rate at which air is introduced into the wastewater through aeration equipment is a primary factor affecting oxygen distribution. A higher aeration rate increases the amount of oxygen available in the system, enhancing the efficiency of aerobic biological processes. However, excessive aeration can lead to energy wastage and operational inefficiencies. The length-to-width (L/W) ratio is a critical parameter in the efficiency of biological processes in wastewater treatment plants (WWTPs). Generally, this ratio is maintained between 5 and 10. The primary reason for this is to facilitate the creation of both aerobic and anoxic conditions within the tanks. Long tanks can create regions with high and low oxygen levels, ensuring the effective use of oxygen in biological processes. In short tanks, creating these different oxygen regions is challenging, resulting in nitrification and denitrification processes occurring in the same area. This situation leads to insufficient elevation of oxygen levels, which can reduce the efficiency of biological processes. In carousel reactors, careful management of dissolved oxygen (DO) levels when the L/W ratio is low significantly improves nitrogen and phosphorus removal. Nitrogen removal relies on nitrification and denitrification processes. During nitrification, ammonium is oxidized to nitrite and then to nitrate, requiring high DO levels. Low DO levels can reduce the nitrification rate, leading to ammonium accumulation. In the denitrification process, nitrate is reduced to nitrogen gas under anoxic conditions. Careful management of DO levels allows both nitrification and denitrification to occur in the same tank, reducing operational costs while increasing nitrogen removal efficiency. Optimizing the L/W ratio in WWTPs enhances the efficiency of biological processes and reduces energy consumption. Proper placement of aeration equipment and adjustment of operating parameters ensure that DO levels are maintained within the desired ranges. Dynamic DO control systems, which monitor biological activity in real-time and automatically adjust DO levels based on this activity, further improve nitrogen and phosphorus removal efficiency. This not only ensures compliance with environmental regulations but also increases energy efficiency, reduces operational costs, and contributes to sustainable wastewater management practices. Therefore, it is crucial to balance the

aeration rate to meet the oxygen demand of the microorganisms without over-aerating the system.

- *Mixing Intensity:* Proper mixing is essential for uniform oxygen distribution throughout the treatment tank. The intensity of mixing in carousel systems ensures that oxygen is evenly dispersed and prevents the formation of zones with low oxygen concentration. Adequate mixing also helps in maintaining a homogeneous mixture of activated sludge and wastewater, ensuring that all microorganisms have equal access to oxygen.

- *Temperature:* The temperature of the wastewater affects the solubility of oxygen. Colder temperatures increase the solubility of oxygen in water, leading to higher concentrations of dissolved oxygen. Conversely, higher temperatures reduce oxygen solubility, which can limit the availability of oxygen for aerobic processes. Temperature fluctuations can also impact the metabolic rates of microorganisms, further affecting their oxygen consumption.

- *Organic Load:* The organic load of the incoming wastewater determines the oxygen demand of the system. A higher organic load requires more oxygen for the degradation of organic pollutants by aerobic microorganisms. As the organic load increases, the oxygen distribution must be adjusted to ensure that there is sufficient oxygen available to meet the increased demand.

- *Wastewater Composition:* The composition of the wastewater, including the presence of toxic substances or inhibitors, can affect the activity of the microorganisms and their oxygen consumption rates. Certain chemicals or compounds in the wastewater may inhibit the metabolic processes of the microorganisms, leading to reduced oxygen uptake and inefficiencies in the treatment process.

- *System Design:* The design of the carousel system, including the placement of aeration equipment and the configuration of the treatment tank, influences oxygen distribution. Proper design ensures that there is adequate aeration and mixing throughout the system, preventing dead zones where oxygen levels are insufficient for biological treatment.

- *Operational Parameters:* Operational parameters such as hydraulic retention time (HRT) and sludge age can also impact oxygen distribution. These parameters affect the residence time of the wastewater and activated sludge in the system, influencing the oxygen demand and distribution dynamics.

The optimization of these factors is essential for the effective operation of carousel systems. Advanced control systems and real-time monitoring technologies can play a significant role in achieving optimal oxygen distribution. By continuously monitoring dissolved oxygen levels and adjusting aeration and mixing rates in response to changing conditions, wastewater treatment plants can ensure that their carousel systems operate at peak efficiency. So, carousel systems are a highly effective and efficient method for the biological treatment of wastewater. Their unique design and the critical role of oxygen distribution in these systems ensure that wastewater is treated to high standards, removing organic pollutants, nitrogen, and phosphorus. The continued development and optimization of carousel systems, including advanced monitoring and control technologies, will be vital for meeting the evolving challenges of wastewater treatment and environmental protection.

2.4 Discharge Standards in the EU Urban Wastewater Treatment Directive

The European Union has introduced a revised directive for urban wastewater treatment, aiming to enhance water quality and environmental protection. The directive includes new, stricter standards for key pollutants such as Total Phosphorus (TP) and Total Nitrogen (TN). These changes are crucial for reducing eutrophication and protecting aquatic ecosystems.

Total Phosphorus (TP)

Proposed New Standard: 0.5 mg/l

Phosphorus is a critical pollutant in wastewater due to its role in eutrophication, which leads to excessive growth of algae and other aquatic plants. This process can deplete oxygen levels in water bodies, harming aquatic life and degrading water quality.

Previously, the standards for TP were less stringent, typically around 1-2 mg/l for larger treatment plants. While these standards helped in reducing phosphorus levels, they were not sufficient to completely mitigate the risks of eutrophication in sensitive water bodies. The proposed new standard of 0.5 mg/l is significantly more stringent. This tighter limit will necessitate the adoption of advanced phosphorus removal technologies in wastewater treatment plants. The implementation of this standard aims to:

- Reduce Eutrophication: By lowering phosphorus concentrations, the growth of algae and aquatic plants will be controlled, preventing oxygen depletion and maintaining healthy aquatic ecosystems.

- Protect Water Quality: Cleaner effluent discharged into water bodies will help in maintaining high water quality standards, making water safer for recreational and other uses.

- Enhance Ecosystem Health: Improved water quality will support the overall health of aquatic ecosystems, promoting biodiversity and resilience.

Total Nitrogen (TN)

Proposed New Standard: 6 mg/l

Nitrogen in its various forms (organic nitrogen, ammonium, nitrate, and nitrite) is another major contributor to eutrophication. High nitrogen levels can also lead to the formation of harmful algal blooms, which can produce toxins affecting both aquatic life and human health.

Previously, the standards for TN were around 10-15 mg/l, depending on the size of the treatment plant. While these standards contributed to nitrogen reduction, they were insufficient for preventing all eutrophication-related problems, especially in sensitive areas.

The new proposed standard of 6 mg/l represents a more aggressive approach to nitrogen removal. Key benefits and goals of this standard include:

- Mitigating Harmful Algal Blooms: By reducing nitrogen levels, the risk of harmful algal blooms is minimized, protecting aquatic life and human health.

- Improving Water Quality: Lower nitrogen levels will lead to cleaner effluent, improving the quality of receiving waters and making them safer for various uses.

- Supporting Ecosystem Stability: Reduced nitrogen concentrations will help maintain ecological balance, supporting diverse and resilient aquatic ecosystems.

The new discharge standards for Total Phosphorus (TP) and Total Nitrogen (TN) in the EU directive represent a significant step forward in environmental protection and water quality management. By setting stringent limits of 0.5 mg/l for TP and 6 mg/l for TN, the directive aims to combat eutrophication, protect aquatic ecosystems, and ensure cleaner, safer water for all uses.

Achieving compliance with these standards will necessitate substantial technological advancements in wastewater treatment processes. This includes the development and implementation of more efficient nutrient removal technologies, as well as the optimization of existing systems. Moreover, it will require significant investment in infrastructure upgrades and ongoing maintenance to ensure that treatment plants can consistently meet the new requirements. Collaboration among member states is crucial for the successful implementation of these standards. Sharing knowledge, best practices, and technological innovations will be essential in overcoming the challenges associated with nutrient removal. Additionally, coordinated efforts in monitoring and enforcement will be necessary to ensure that all member states adhere to the directive, thereby achieving the collective goal of a healthier and more sustainable environment. Ultimately, the implementation of these stringent TP and TN discharge limits will lead to cleaner and safer water bodies, benefiting not only the natural environment but also public health and the economy. This directive underscores the EU's commitment to environmental stewardship and highlights the importance of proactive measures in safeguarding water quality for current and future generations (European Commission, 2022).

2.5 Process Modelling and Simulation for Design and Operation

Process modeling and simulation have become indispensable tools in the wastewater treatment plant (WWTP) design and operation, enabling engineers and researchers to predict system behavior under various conditions, optimize performance, and make informed decisions. This approach is particularly relevant in the context of activated sludge systems, where the complex interactions between biological, chemical, and physical processes need to be accurately represented.

One of the primary goals of process modeling in wastewater treatment is to develop a mathematical representation of the treatment processes, which can be used to simulate the behavior of the WWTP. These models typically include a set of differential equations that describe the kinetics of biological reactions, the transport of substances, and the settling of solids. The Activated Sludge Model No. 1 (ASM1) is a widely used framework in this regard, providing a basis for modeling the biological processes of nitrification and denitrification, which are crucial for nitrogen removal in activated sludge systems (Henze et al., 1987).

Simulation tools, such as the SuperModel (SUMO), offer a practical platform for applying these models to real-world scenarios. SUMO is a dynamic simulation software that allows for the integration of various process models, including those for activated sludge systems, and provides a user-friendly interface for setting up and running simulations (Nopens et al., 2010). By using SUMO, engineers can test different operational strategies, such as adjusting aeration rates or modifying sludge retention times, to evaluate their impact on treatment efficiency and energy consumption. SUMO is fundamentally based on Activated Sludge Model (ASM) concepts, but it significantly expands the model scope to cover more detailed biological reactions, ionic species equilibrium for pH estimation, and gas transfer phenomena typically linked with aeration systems (Nishida & Ohtsuki, 2020).

SUMO has been utilized for the systematic performance evaluation of reinforcement learning algorithms applied to wastewater treatment control optimization, demonstrating its potential for advanced control and optimization strategies in WWTPs (Croll et al., 2023). In addition to its application in process modeling and simulation, SUMO has been employed for the prediction of wastewater quality parameters at the WWTP inlet, showcasing its utility in predicting and optimizing influent quality and quantity (Wodecka et al., 2022; Wang et al., 2021). Moreover, SUMO's capabilities extend to soft sensor applications for the estimation of plant effluent concentrations, demonstrating its potential for real-time monitoring and control of WWTP processes. The use of SUMO in the analysis of performance and operational parameters of biological trickling filters and sequencing batch reactors further underscores its significance in evaluating the efficiency and effectiveness of various treatment technologies (Liang et al., 2021; Alagha et al., 2020). The development of commercial software and simulators, including SUMO, has significantly contributed to the optimization of design, operation, and control of wastewater treatment processes, reflecting the pivotal role of SUMO in advancing the technological capabilities of WWTPs (Yang & Belia, 2022). The SuperModel (SUMO) has emerged as a comprehensive and advanced platform for wastewater treatment plant modeling and simulation, offering diverse applications in process evaluation, control optimization, influent prediction, and real-time monitoring. Its integration with state-of-the-art technologies underscores its pivotal role in advancing the efficiency and sustainability of WWTP operations.

3. MATERIALS AND METHOD

This study provides a thorough evaluation of the WWTP in the Black Sea Region by utilizing advanced process simulation tools. The aim is to assess both the design and operational efficiency of the plant, ensuring it meets regulatory standards and operates optimally under different conditions. By leveraging simulation tools, this study aims to provide a detailed understanding of how the plant performs across different scenarios, offering insights that can guide future improvements and operational adjustments.

Key metrics such as effluent quality, sludge production, and oxygen demands were systematically assessed against the plant's design documents and simulation results. Effluent quality is a critical measure of the plant's effectiveness in removing contaminants from wastewater before it is discharged into the environment. High effluent quality indicates that the plant is successful in meeting regulatory standards for pollutants such as COD, TSS, TN, and TP. By comparing actual effluent quality data with simulation results, this study evaluates whether the plant operates within acceptable limits and identifies any deviations that need to be addressed.

3.1   Wastewater Treatment Plant Design Information

The detailed design and operational configuration of the studied Wastewater Treatment Plant (WWTP) are meticulously outlined in this section. The process begins with the headworks, where the wastewater undergoes a sequence of treatment stages designed to ensure the optimal reduction of pollutants. This sequential approach is essential for protecting downstream processes, enhancing overall treatment efficiency, and meeting regulatory discharge standards.

Grit-Grease Chamber

The first stage in this treatment sequence is the grit-grease chamber, a critical component that primarily removes grit and grease from the incoming wastewater. Grit and grease are common contaminants in domestic and industrial wastewater that can cause significant operational issues if not removed early in the treatment process. The

grit-grease chamber protects downstream processes from abrasion and excessive maintenance by capturing these coarse materials. This preliminary treatment step ensures that subsequent biological and mechanical processes operate more efficiently and with less wear and tear.

Bio-P Reactors

After the grit-grease chamber, the wastewater flows into a series of Bio-P reactors. These reactors are specifically engineered to facilitate biological phosphorus removal (BPR), a process that enhances the removal efficiencies of nutrient loads from the wastewater. In the Bio-P reactors, polyphosphate-accumulating organisms (PAOs) play a crucial role. Under alternating anaerobic and aerobic conditions, PAOs uptake and store phosphorus, which is later removed from the system as part of the sludge. This biological approach to phosphorus removal is both effective and environmentally sustainable, reducing the need for chemical additives.

Carousel Reactors

Following the Bio-P reactors, the flow of wastewater is directed through Carousel reactors. These reactors are implemented for their efficacy in providing extended aeration and efficient mixing, thereby promoting biological nutrient removal. The unique design of Carousel reactors, characterized by their oval or circular shape, creates a continuous racetrack-like flow pattern. This design ensures that the wastewater and activated sludge are thoroughly mixed, maximizing the contact time between microorganisms and pollutants. In these reactors, nitrification (conversion of ammonia to nitrate) and denitrification (conversion of nitrate to nitrogen gas) occur, effectively reducing nitrogen levels in the wastewater.

Final Clarifiers

The next phase of treatment involves the final clarifiers. These units are pivotal in the separation of biomass from the treated water. The clarified effluent is extracted from the top of the clarifiers, while thickened sludge settles at the bottom. The design of the clarifiers ensures that solids are efficiently removed from the wastewater, preventing carryover into the final effluent. This separation process is essential for producing high-quality effluent that meets discharge standards.

Disc Filtration Unit

After passing through the final clarifiers, the clarified effluent undergoes further polishing in a disc filtration unit. This unit serves as an additional barrier to remove suspended solids and other particulates, ensuring that the effluent is free from residual

contaminants. The disc filtration process improves the overall clarity and quality of the treated water, making it suitable for discharge or potential reuse applications. The integration of disc filtration units into the wastewater treatment process also supports compliance with regulatory requirements. Environmental regulations often mandate strict limits on suspended solids and other contaminants in discharged effluent to protect water quality and public health. By incorporating disc filtration, treatment plants can consistently meet these regulatory standards.

Sludge Processing Line

In parallel with the liquid treatment line, the WWTP includes a dedicated sludge processing line. This line begins with mechanical thickeners, which concentrate the sludge by removing excess water. Thickening the sludge reduces its volume, making subsequent handling and processing more efficient. Following thickening, the sludge undergoes dewatering, which further reduces its volume and moisture content. Dewatered sludge is easier to manage and dispose of, and it can also be treated further for resource recovery or safe disposal.

Operational Configuration

The layout of the treatment facility is designed for optimal capacity and reliability, with three Bio-P reactors, three Carousel tanks, and three final clarifiers operating in parallel. This parallel configuration enhances the plant's ability to handle varying wastewater loads and provides redundancy, ensuring consistent performance even if one unit requires maintenance. Additionally, the process design incorporates the recycling of RAS, which is redirected back to the head of the Bio-P tanks. This recirculation is crucial for maintaining activated sludge biomass levels within the system, ensuring consistent microbial activity and treatment performance.

The detailed design and operational configuration of the studiedWWTP in the Black Sea Region highlight the sophisticated and integrated approach to wastewater treatment. Each stage of the treatment process is carefully designed to optimize pollutant removal, protect downstream processes, and ensure compliance with regulatory standards. By combining advanced biological treatment methods with robust mechanical processes, the plant achieves high levels of efficiency and reliability. This comprehensive evaluation underscores the importance of continuous monitoring, optimization, and innovation in wastewater treatment to protect water quality and support sustainable environmental management.

3.1.1 Design flowrates and wastewater characterization

Table 3.1 provided below offers a comprehensive summary of the flow rates and the minimum process temperatures stipulated in the design specifications of the WWTP. Previously, the standards for Total Nitrogen (TN) were typically in the range of 10-15 mg/l, varying with the treatment plant's size. Although these standards helped reduce nitrogen levels, they were not adequate to fully prevent eutrophication issues, particularly in vulnerable regions. The newly proposed standard of 6 mg/l signifies a more stringent and proactive strategy for nitrogen reduction.

The design parameters include a maximum flow rate of 1085 m^3/hour, which corresponds to a peak factor (PF) of 2.15. This peak factor is indicative of the system's capacity to handle surge flows effectively, thereby ensuring stable operation during varying influent conditions. Furthermore, the operational design temperatures are set to range from a minimum of 12°C to a maximum of 25°C, reflecting the thermal tolerances required for optimal biological activity within the treatment processes.

The flow rates to the plant's design are determined 868.50 m^3/day and and 952.50 m^3/day for the respective design stages. From primary sedimentation tanks to biological reactors and secondary clarifiers, each component must be appropriately sized to handle the specified volumes of wastewater. This ensures that each stage of the treatment process operates within its optimal capacity, enhancing overall treatment efficiency and effectiveness. These values are crucial for ensuring that the plant's hydraulic and treatment capacities are aligned with anticipated daily and seasonal variations in wastewater volumes, thereby facilitating compliance with the prescribed effluent quality standards.

Table 3.1. Flowrates of wastewater treatment plant used in design.

Flowrate	Unit	Stage 1: Year 2032	Stage 1: Year 2047
Average Flow, Q_{DWF}	m^3/day	11,132	12,177
	m^3/hour	463.83	507.38
Maximum wet weather flowrate, Q_{PWD}	m^3/hour	987.82	1085.80
Design Flowrate, Q_D	m^3/hour	868.50	952.50

Table 3.2 presents the characteristics of the influent wastewater, as specified for dry weather flow (DWF) conditions within the design framework. The ratio of influent COD (Chemical Oxygen Demand) to TKN (Total Kjeldahl Nitrogen) is deemed appropriate for achieving total nitrogen removal through the SNdN method of activated sludge treatment, as noted by Henze et al. (2008).

Table 3.2. Raw influent wastewater characterization and discharge limits for studied WWTP.

Flowrate	Unit	Stage 1 2032	Stage 2 2047	Discharge Limits
BOD$_5$	mg/L	259	270	<25
COD	mg/L	517	538	<125
TSS	mg/L	265	275	<35
TN	mgN/L	43	45	<15
TP	mgP/L	8.6	9.1	<2

3.1.2 Process design data

Initially, following the de-gritting stage, the raw wastewater is channeled into Bio-P reactors, designed specifically for enhanced biological phosphorus removal. This initial step is crucial for preparing the wastewater for subsequent treatment stages. Post Bio-P treatment, the wastewater progresses to carousel type activated sludge reactors, which play a significant role in further purification.

The dimensions and operational capacities of these bioreactors have been adapted according to the flow rates and pollutant loads projected for Stage 2 (anticipated for the year 2047). The Bio-P unit has a substantial volume of 1353.14 cubic meters, with the tank depth standardized at 4.5 meters to accommodate the specific treatment needs. Additionally, a chemical dosage system is integrated with the Bio-P reactor to serve as a back-up mechanism for phosphorus removal.

The carousel reactors have a capacity of 21.000 m^3 in total. The activated sludge has 3 equal parallel lanes. The anoxic sections are spatially generated by regulation of aeration in bioreactors. The aerobic reactor is bubbled with membrane diffusers tiled on the floor of carousel reactors (Figure 3.2). The dissolved oxygen sensors were used to control oxygen profile for biological nitrogen removal. The total sludge age of the

system is 25 days. The activated sludge unit was equipped with 4 (3+1) blowers with a capacity of 1250 m^3_{air}/hour. The general layout of the system is given below.
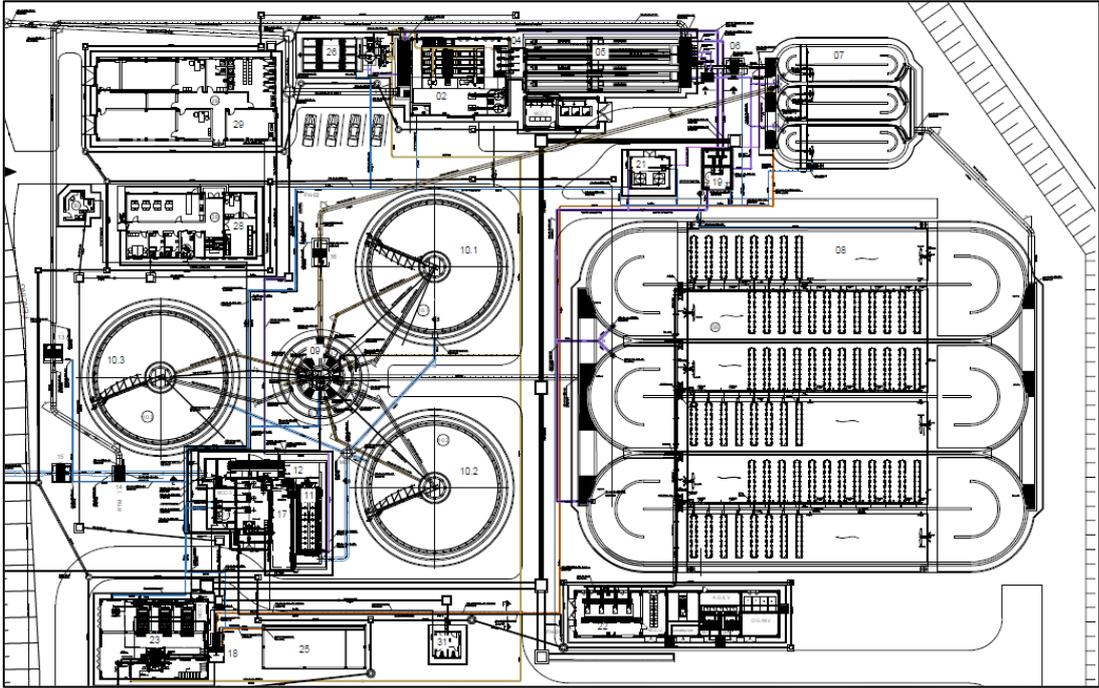
Figure 3.1. General layout of studied WWTP.

The dissolved oxygen (DO) concentration is controlled from 2 points of the reactor. The aeration is controlled according the (weighted) average measurement values obtained from DO probes. The same control strategy is applied for other reactors, individually. Online nitrate sensor is mounted at the outlet of the reactor to monitor effluent nitrate concentration. The ORP is installed at the end of anoxic period.
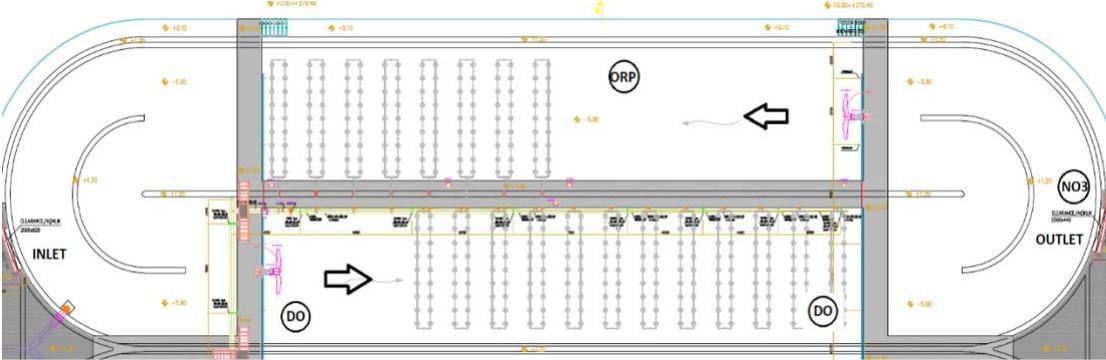
Figure 3.2. Diffuser arrangement in carousel reactor (1 of 3).

The system has 3 final clarifiers with a total surface area of 940 m^2. The diameter and side water depth of each clarifier is 20 m and 3.5 m, respectively. The effluent is

subjected to microfiltration to obtain clarified effluents free of total suspended solids concentration. The hydraulic capacity of filtration unit is 500 m³/hour. The sludge is collected in pumping station for both recycling back to the Bio-P reactors and excess sludge wastage. The excess sludge flow rate is reported to be 345 m³/day. (Process Report, April 2021). The waste sludge is thickened and dewatered followed by solar drying system.

3.1.3 Performance requirements

Table 3.3 comprehensively summarizes the discharge limits and the required removal efficiencies for various key parameters, including BOD₅, COD, TSS, TN, and TP. The regulatory framework specifies discharge limits for nitrogen and phosphorus to mitigate their environmental impact. To adhere to these regulations, the treatment facility must achieve significant removal efficiencies. The required removal efficiency for total nitrogen is approximately 79%, which involves a comprehensive treatment strategy integrating both nitrification and denitrification processes to effectively reduce nitrogen levels. For total phosphorus, the required removal efficiency is about 91%. Therefore, wastewater treatment system design and operation processes at the facility are meticulously calibrated to ensure that these parameters are consistently met, thereby contributing to the overall sustainability and environmental stewardship of the community.

Table 3.3. Required removal efficiencies for conventional parameters.

Parameter	Unit	Design criteria (inlet) Year 2032	Design criteria (inlet) Year 2047	Discharge limit (outlet)	Minimum Removal efficiency, %
BOD₅	mg/L	259	270	25	90
COD	mg/L	517	538	125	76
TSS	mg/L	265	275	35	-
Total N	mgN/L	43	45	15	65
Total P	mgP/L	8.6	9.1	2	78

3.2 Simulation Approach

3.2.1 Influent wastewater characterization

The influent wastewater characterization is adopted from the previous simulation studies conducted in Turkey (Insel et al., 2020; 2021). These foundational simulations provide a detailed breakdown of the wastewater components, crucial for accurate modeling and design of treatment processes. The specific fractionation of COD in the influent, pivotal for determining the treatment strategies, is succinctly summarized in Table 3.4. This table plays a crucial role in the study as it categorizes COD into readily biodegradable, slowly biodegradable, and inert fractions, each requiring different treatment approaches. Additionally, the study adopts specific ratios from the simulation data for key nitrogen and phosphorus fractions in the wastewater. The ratio of NH_4 to total TKN is set at 65%, reflecting the bioavailable nitrogen that primarily influences the nitrification and denitrification processes in biological treatment systems. Similarly, the ratio of PO_4-P to TP is accepted at 53%, indicating the proportion of phosphorus that is readily available for biological uptake or chemical removal.

Table 3.4. Influent COD fractionation of studied WWTP.

COD fraction	Acronym	Concentration	% fraction of C_T
Total COD	C_T	538	-
Filterable OD	S_T	215	40
Particulate COD	X_T	323	60
Volatile Fatty Acids COD	S_A	55	10
Readily Biodegradable COD*	S_s	42	8
Soluble inert COD	S_I	32	6
Particulate inert COD	X_I	54	10
Slowly biodegradable COD	X_S	252	47
Inorganic fixed solids	X_F	83	-

*non-VFA.

3.2.2 Model selection and implementation

General activated sludge model (Sumo Model No.1) encrypted in SUMO was used to simulate the treatment performance of the design. Simply, the model comprises nitrification/denitrification processes together with aerobic carbon degradation, enhanced biological phosphorus and chemical phosphorus removal (ferric, alum etc.) processes (Melcer et al., 2003). The related kinetic parameters incorporated in expressions have temperature correction factors. The aeration was also modelled by introducing relevant parameters as described in design documents (Figure 3.3). The simulation philosophy and implementation in software were summarized as follows:

1. The model layout and mass balancing were provided according to design report.

2. A grit-grease removal unit was incorporated in layout to facilitate 2% increase in organic fraction in the influent.

3. The Bio-P reactors were operated in parallel, so 3 lanes are combined in one reactor to reduce simulation time.

4. Since each reactor has individual control system the carousel reactors are split into 3 reactors as of design documents.

5. The carousel reactors were simulated with 10 reactors in series according to approach suggested by Abusam et al. (1999) (Figure 3.3). Recirculation with slow-speed mixers in simulated by internal recirculation set by side flow divider (Figure 3.4).
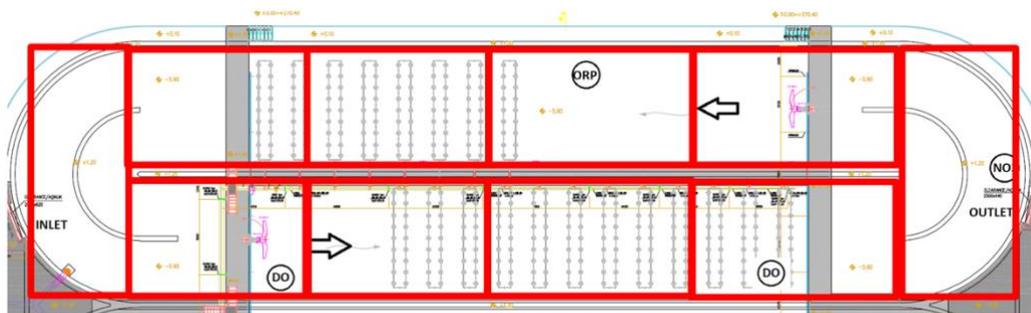

Figure 3.3. Staging of carousel reactor with 10-reactor in series configuration

6. The DO concentration is measured in CSTR5 and CSTR9. The average DO is calculated and PID control provides real time air flow regulation. The air can be distributed to the reactors depending upon diffuser capacity as shown in Figure 3.4.
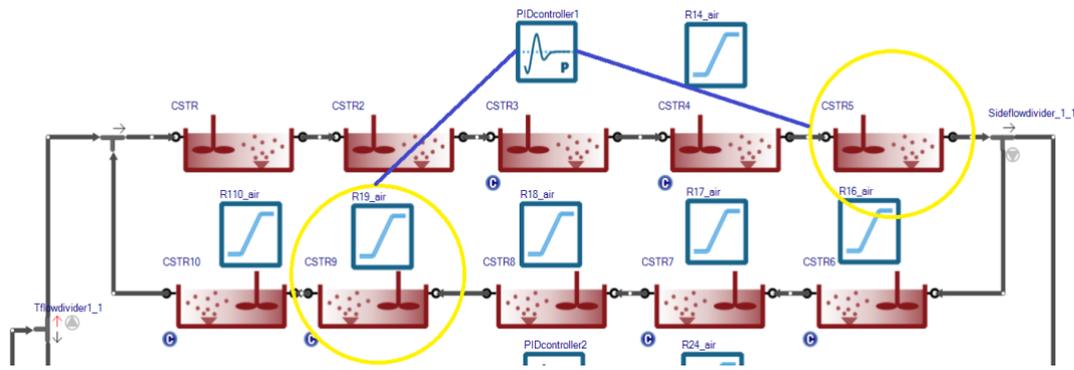
Figure 3.4. Dissolved oxygen control in carousel reactor.

7. The RAS rate has a proportional control system linked to influent flowrate measurements (set to 70%).

8. Sludge wastage is manually regulated from RAS line.

9. The sludge is sequentially thickened and dewatered with solids percent removal of 93% and 95%, respectively.

10. Effluent dry solids content of the sludge is set to 22%.

A double exponential settling model (Takacs et al., 1991) was selected for simulation of sludge distribution over activated sludge units and final clarifiers. The final clarifier is divided into 9 equal compartments where the top and the bottom represents the effluent and RAS line, respectively. The (default) kinetic and stoichiometric parameters used in process simulation were given in Annex Section. The plant layout for design and simulation are shown in Figure 3.1 and Figure 3.2. The relevant information regarding model implementation is provided in ANNEX section.

Simulation study had 4 steps to obtain steady-state calculations:

- Preparation of influent wastewater file including COD, N, P fractions as well as influent flowrate.

- Preparing plant simulation layout and all sludge/water recirculation in order to set mass balances.

- Incorporation of info on volumes, operational conditions (aerated/unaerated, DO set points etc.) as well as sludge wastage rates.

- Data entry of sludge thickeners and solids capture rates of relevant units.

- Running of steady state calculation during at least 70 days (>3×SRT) to reach stable process performance.

4. RESULTS AND DISCUSSION

The steady-state process simulation results indicated that the effluent total nitrogen of TN<6 mgN/L could be achieved with average flowrate and influent characterization provided in process design. The effluent ammonia nitrogen (NH_4-N) was always below 0.7 mgN/L with default model parameters (Annex Section). In this respect, the effluent quality with respect to TN could be achieved with current operation strategy of wastewater treatment plant facility.
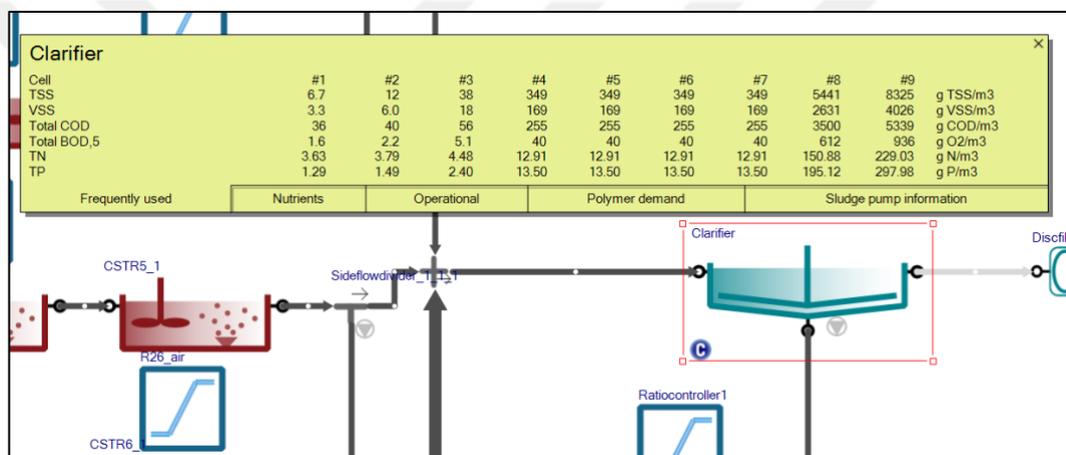
Figure 4.1. Simulation of components in stratified final clarifier.

The clarifier design was made on the basis of ATV131 design (2000). The MLSS concentration in RAS was calculated using thickening time in final clarifiers (Figure 3.6). The reading of Figure 3.6 at SVI=110 L/kg corresponds to a settled sludge concentration (SS_{BS}) of 11.8 kg/m^3. The RAS will contain more diluted sludge concentration with a dilution factor of 70%, caused by short circuiting due to scraper facilities (ATV131,2000). As a result; X_{RAS}= 70% · 11.8 = 8.26 kg/m^3 can be found in RAS according to ATV131. This value is in good agreement with the simulation result obtained as 8.32 kg/m^3 for Stage 1 and Stage 2. Overall plant configuration is illustrated in Figure 3.7.
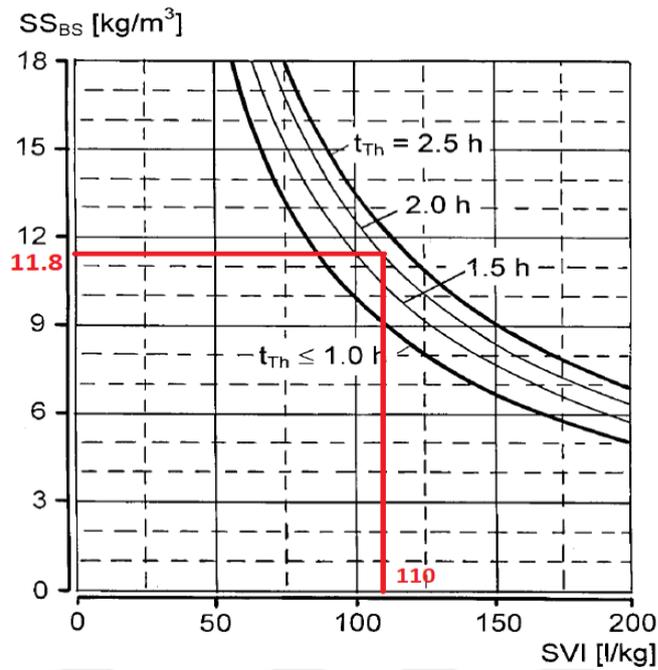
Figure 4.2. MLSS (SS_{BS}) concentration in settled sludge as a function of SVI and sludge thickening time.

The simulation of Stage 1 in the wastewater treatment process involves analyzing various concentration parameters to assess the effectiveness of the treatment stages. Table 4.1 shows Simulation results for STAGE 1 in concentrations.

Table 4.1. Simulation results for STAGE 1 (Concentrations).

Symbol	Influent	Clarifier Effluent	Disc Filter Effluent	Reject Output	WAS Pumped	Clarifier Sludge	Unit
COD	517.0	36.0	32.1	504.7	5302.1	5302	g COD/m^3
TSS	265.6	5.7	0.1	271.2	7539.7	7539	g TSS/ m^3
VSS	185.9	2.9	0.1	189.0	3899.6	3899	g VSS/ m^3
BOD_5	260.8	1.7	0.9	247.0	1076.1	1076	g O_2/ m^3
TN	43.0	3.4	3.2	41.2	238.2	238.2	g N/ m^3
NH_4	28.0	0.7	0.7	26.0	0.7	0.7	g N/ m^3
NO_x	0.0	1.6	1.6	0.1	1.6	1.6	g N/ m^3
TP	8.6	1.8	1.6	9.2	256.4	256.4	g P/ m^3
PO_4	5.6	1.5	1.5	5.3	1.5	1.5	g P/ m^3
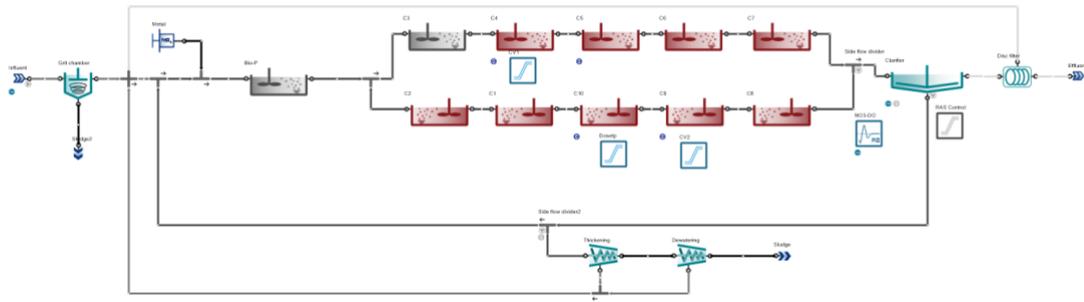
Figure 4.3. Simulation layout of WWTP (SUMO^{TM}-Dynamita).

Table 4.1 shows Simulation results for STAGE 2 in concentrations.

Table 4.2. Simulation results for STAGE 2 (Concentrations).

Symbol	Influent	Clarifier Effluent	Disc Filter Effluent	Reject Output	WAS Pumped	Clarifier Sludge	Unit
COD	538.0	37.5	33.3	526.6	5334.3	5334.3	g COD/m^3
TSS	276.4	6.1	0.1	283.2	7562.4	7562.4	g TSS/ m^3
VSS	193.5	3.1	0.1	197.3	3921.7	3921.7	g VSS/ m^3
BOD$_5$	271.4	1.7	0.9	257.7	1096.0	1096.0	g O$_2$/ m^3
TN	45.0	4.0	3.8	43.2	241.3	241.3	g N/ m^3
NH$_4$	29.3	0.6	0.6	27.3	0.6	0.6	g N/ m^3
NO$_x$	0.0	2.2	2.2	0.1	2.2	2.2	g N/ m^3
TP	9.6	2.3	2.1	10.2	256.7	256.7	g P/ m^3
PO$_4$	6.2	2.0	2.0	6.0	2.1	2.1	g P/ m^3

The flowrates together with mass loading of COD, TSS, Nitrogen and Phosphorus species in (1) influent (2) Clarifier effluent (3) Filtration effluent (4) Return flows from thickening/dewatering were summarized in Appendix Section (Table A.3 and Table A.4).

Additional simulation was conducted for the composite wastewater sample analyzed in 19/08/2021. The analysis results are given in Appendix section. Shortly, the influent wastewater COD, TKN and TP concentrations were introduced to the simulation program. Table 4.3 below summarized the steady state concentrations at each unit of studied WWTP. The flowrate of Stage 2 is used in simulation to express the maximum hydraulic capacity of the plant.

The effluent quality of the plant was found to be under the discharge limits of COD, TSS, TN and TP. It should be noted that no chemical precipitants were required to meet the effluent TP standard with the wastewater analyzed. The airflow rate was calculated to be 78,000 m^3/day at summer conditions (25°C).

Table 4.3. Simulation results using real wastewater characterization (sampled at 19/08/2021).

Symbol	Influent	Clarifier Effluent	Disc Filter Effluent	Reject Output	WAS Pumped	Clarifier Sludge	Unit
COD	640.0	44.3	39.5	626.7	6436	6436	g COD/m^3
TSS	328.8	6.3	0.1	333.7	8348	8348	g TSS/ m^3
VSS	230.1	3.5	0.1	234.4	4644	4644	g VSS/ m^3
BOD$_5$	322.8	1.9	0.9	306.9	1384	1384	g O$_2$/ m^3
TN	53.0	4.7	4.5	51.0	296.5	296.5	g N/ m^3
NH$_4$	34.5	0.7	0.7	32.2	0.7	0.7	g N/ m^3
NOx	0.0	2.6	2.6	0.2	2.6	2.6	g N/ m^3
TP	6.7	0.6	0.5	7.2	218.4	218.4	g P/ m^3
PO$_4$	4.4	0.4	0.4	4.1	0.4	0.4	g P/ m^3

The SUMO program was utilized to dynamically simulate oxygen levels and their impact on nitrification and denitrification processes. In both simulations and real-world applications, oxygen levels were adjusted by regulating the air output from blowers. The simulations dynamically adjusted the amount of air supplied to the entire

reactor, lowering oxygen levels and balancing nitrification and denitrification. The primary objective was to ensure that the plant operates efficiently within the designed parameters and meets the regulatory discharge limits. The results from the dynamic simulations provided critical insights into the behavior of dissolved oxygen (DO) levels and their impact on the biological processes within the reactors. By dynamically adjusting the air supply, the simulations achieved a balance in oxygen levels, crucial for maintaining optimal conditions for both nitrification and denitrification. High oxygen levels promoted nitrification, while low oxygen levels were necessary for effective denitrification, demonstrating the delicate balance required in managing DO levels.
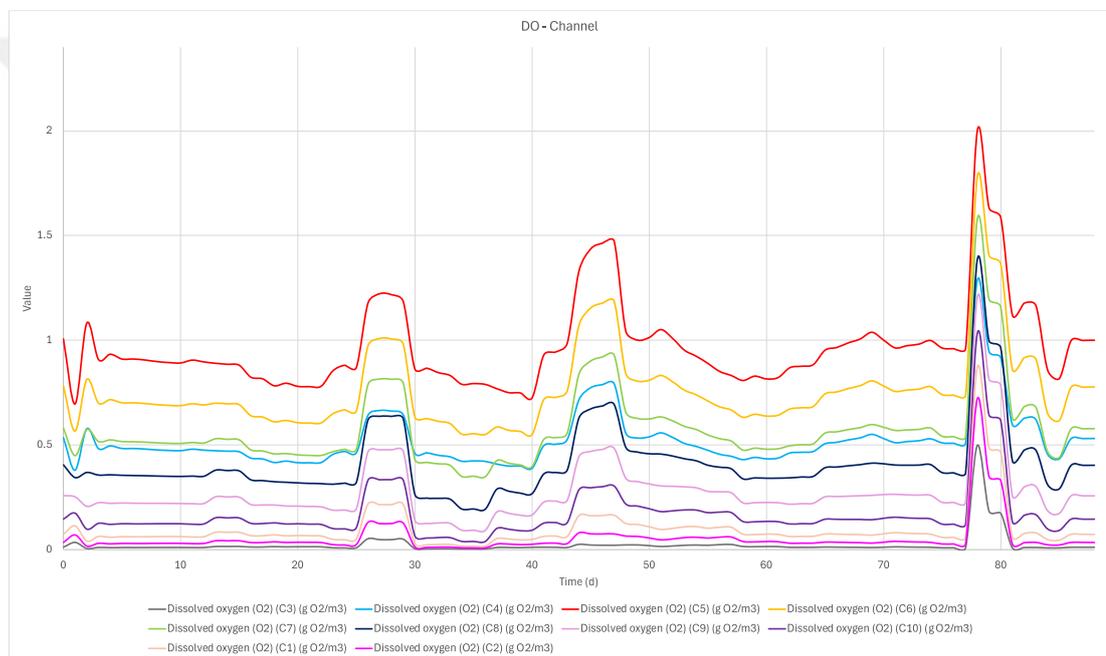
Figure 4.4. DO Concentrations (SUMO™-Dynamita).

Determining the oxygen level is critically important to ensure that both nitrification and denitrification processes can function effectively in the reactor. In simulations and real-world applications, oxygen levels are adjusted by reducing the amount of air supplied to the system via blowers; this adjustment is applied to the entire system, not individually. Lowering the oxygen level also leads to a decrease in nitrate concentrations. This reduction in nitrate can result in less nitrate available for the denitrification process, which in turn can affect phosphorus removal. Therefore, careful adjustment of oxygen levels is necessary to maintain a balance between nitrification and denitrification processes. The SUMO simulation model is an essential

tool for optimizing these processes and improving the operational efficiency of the treatment plant. SUMO simulations, calibrated with real-time data, enhance prediction accuracy and improve operational decision-making processes.
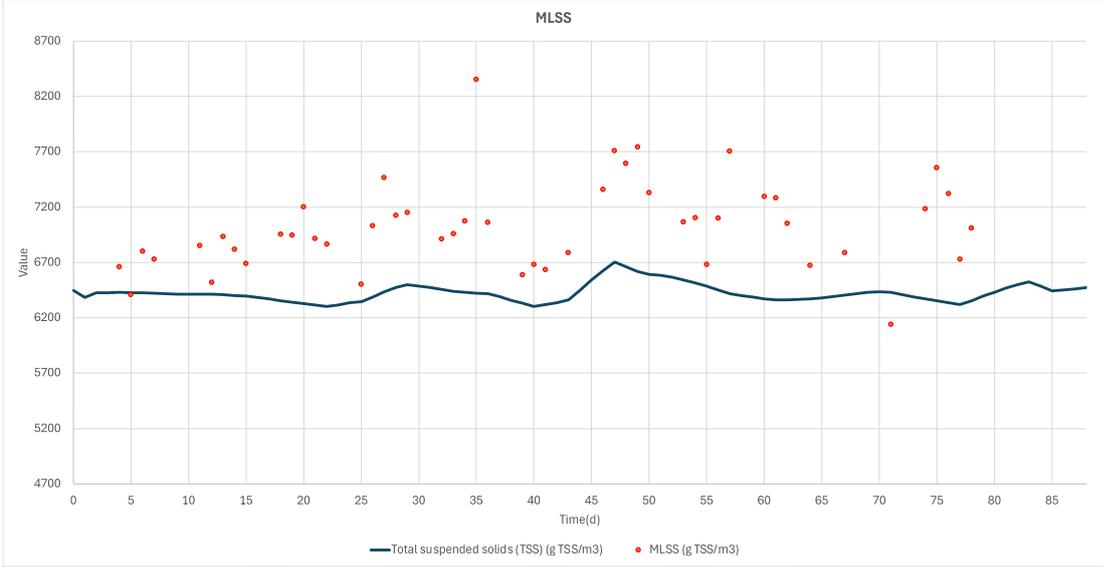

Figure 4.5. Dynamic simulation results - Total Suspended Solids (SUMO^{TM}-Dynamita).

Figure 4.5. shows how the Total Suspended Solids (TSS) concentration changes over a period of 88 days. TSS concentrations range between 6400 and 6800 g TSS/m^3, generally maintaining a stable trend. TSS is directly related to MLSS, a crucial parameter in biological treatment processes. MLSS includes all suspended solids in the bioreactors, such as microorganisms and inorganic particles, and is used to evaluate the efficiency of activated sludge systems. Proper control of MLSS levels is critical for ensuring the effectiveness of biological treatment and maintaining optimal performance of bioreactors. The stability of TSS concentrations within specific limits indicates that the treatment plant is operating efficiently, and that process control is successful.

It is important to note that this graph is the result of a dynamic simulation and that the values closely match the actual data from the plant. Dynamic simulations provide critical tools for predicting plant performance and optimizing processes.
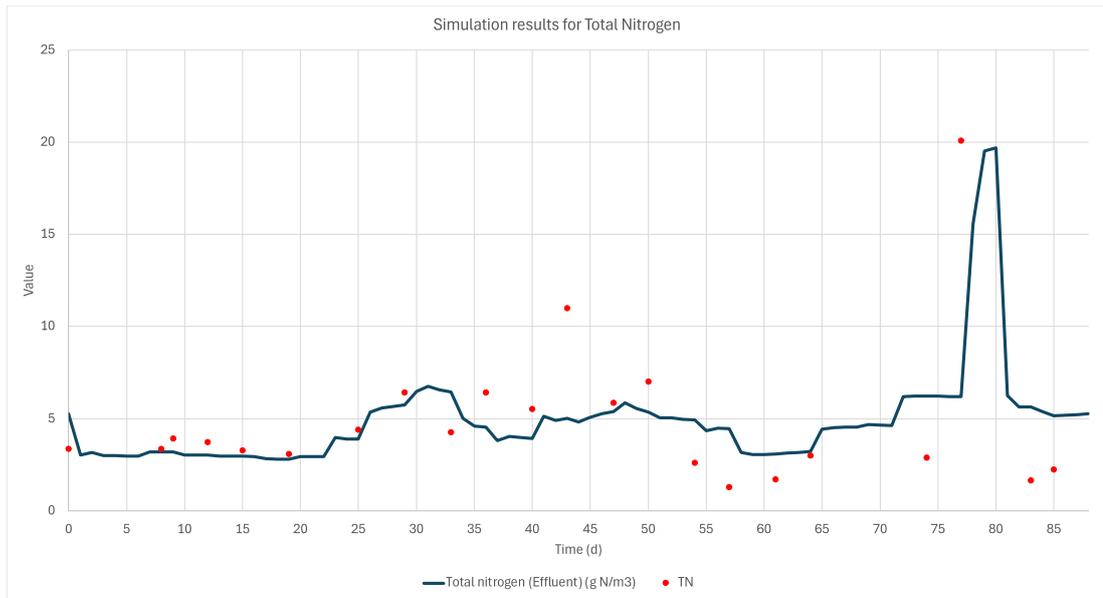
Figure 4.6. Dynamic simulation results - Total Nitrogen (SUMO^{TM}-Dynamita).

Figure 4.6. illustrates the changes in total nitrogen (TN) concentration in the effluent over an 88-day period. The data points represent measured TN concentrations (in g N/m3), while the blue line shows the simulation trend of TN concentration. The graph shows the simulation results of Total Nitrogen (TN) concentration over a period of 88 days. The blue line represents the Total Nitrogen concentration in the effluent (g N/m³), while the red dots represent individual TN measurements. In the initial phase (0-20 days), the Total Nitrogen concentration remains relatively stable around 3 g N/m³. This indicates consistent performance in nitrogen removal during this period. In the intermediate phase (20-50 days), there is a noticeable increase in Total Nitrogen levels between days 25 and 30, reaching approximately 6.5 g N/m³. Following this peak, the concentration drops back to a range of 4-5 g N/m³, indicating an improvement in performance. In the late phase (75-85 days), a significant peak is observed around day 79, where the Total Nitrogen concentration sharply reaches 19.5 g N/m³. This substantial increase is due to nitrogen loading in the system. After this peak, the concentration decreases to approximately 5.2 g N/m³. Overall, the plant maintains Total Nitrogen levels within an acceptable range. Regular fluctuations suggest that the plant is generally effective in nitrogen removal.

This simulation result indicates an improvement in the system's efficiency, likely due to corrective measures taken to optimize aeration and DO levels, or other adjustments in the operational parameters to enhance nitrogen removal processes. The relationship between TN concentration and Mixed Liquor Suspended Solids (MLSS) is crucial.

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Effective control of MLSS levels ensures sufficient biomass for nutrient removal. The graph represents a dynamic simulation closely matching the real operational data from the treatment plant. This alignment demonstrates the robustness of the SUMO simulation model used to predict plant performance and optimize operations. Compared to the EU discharge standards for total nitrogen, the values observed in this graph are well within acceptable limits. Typically, EU discharge standards require TN concentrations in treated effluent to be below 6 mg/L. The consistent TN concentrations observed in the graph indicate that the treatment plant effectively removes nitrogen and complies with the new EU discharge regulations. This emphasizes the importance of continuous monitoring and adaptive management to maintain optimal performance. Ensuring consistent DO levels and promptly addressing any disruptions can prevent peaks in TN concentrations, thus ensuring compliance with regulatory standards. Regular calibration of the simulation model with real-time data can enhance predictive accuracy and operational decision-making, while investigating the causes of slight increases in TN can lead to targeted improvements in the treatment process.

Figure 4.7. Dynamic simulation results - Total Ammonia (SUMO^{TM}-Dynamita).

Figure 4.7. illustrates the changes in total ammonia (NH$_4$) concentration in the effluent over approximately 88 days. The data points represent measured NH$_4$ concentrations (in g N/m^3), while the blue line shows the simulation trend of NH$_4$ concentration. Total ammonia values generally fluctuate between 0.2-0.4 g N/m3, with some days showing

sudden increases and decreases. For example, around day 30, there is a noticeable peak reaching up to 0.612 g N/m3, followed by a decrease. The actual NH4 levels entering the facility are represented by red dots and are generally scattered around the total ammonia curve. On certain days, NH4 levels may be higher or lower than the total ammonia levels. Overall, despite occasional fluctuations in total ammonia levels on the graph, a generally stable level has been maintained. These results highlight the importance of monitoring total ammonia and NH4 levels during the simulation period and the potential impacts of fluctuations in managing these levels. Such analyses provide critical information for assessing and improving the operational efficiency of wastewater treatment plants. The effectiveness of ammonia removal is closely linked to the concentration of MLSS. Consistent MLSS levels ensure sufficient biomass for nitrification. The graph represents a dynamic simulation closely matching the real operational data from the treatment plant, demonstrating the robustness of the SUMO simulation model used to predict plant performance and optimize operations.

This graph emphasizes the importance of continuous monitoring and adaptive management to maintain optimal performance. Ensuring consistent dissolved oxygen levels and promptly addressing any disruptions is necessary to prevent peaks in NH4 concentrations and ensure regulatory compliance. Regular calibration of the simulation model with real-time data can enhance predictive accuracy and operational decision-making, while investigating the causes of mid-period increases in NH4 can lead to targeted improvements in the treatment process.
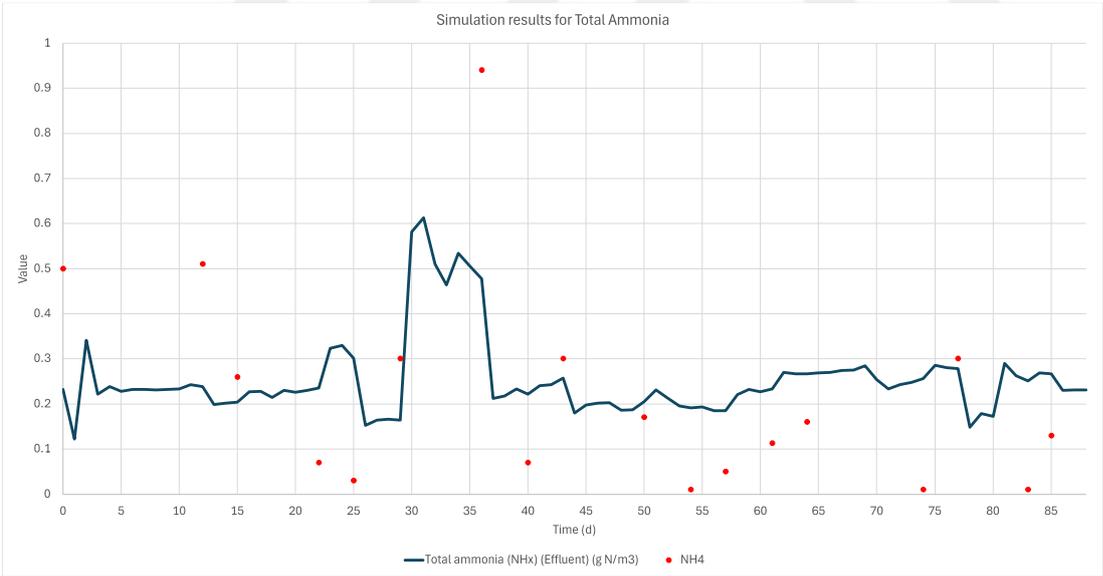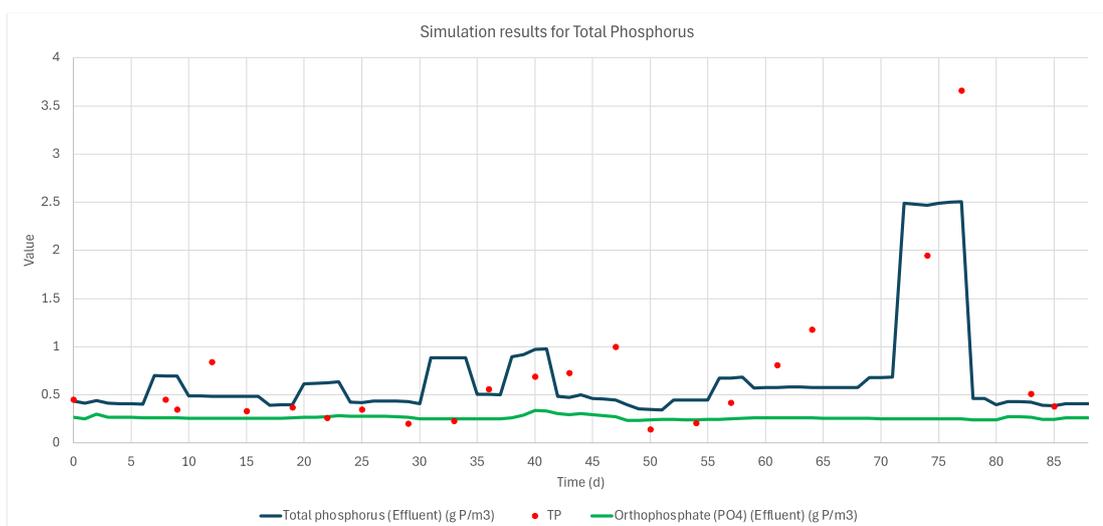

Figure 4.8. Dynamic simulation results - Total Phosphorus (SUMO^{TM}-Dynamita).

Figure 4.8. shows how the concentrations of total phosphorus (TP) and orthophosphate (PO_4) in the effluent change over a period of 88 days. Initially, the TP concentration is approximately 0.4 g P/m^3, while the orthophosphate concentration is around 0.27 g P/m^3. Until day 70, TP concentrations show slight fluctuations but generally remain between 0.4-1.0 g P/m^3. During this period, orthophosphate concentrations stay almost stable between 0.2-0.3 g P/m^3. Around day 70, a significant increase in TP concentration is observed, reaching approximately 2.5 g P/m^3. This increase is due to the rise in phosphorus levels in the influent water. From day 75 onwards, the TP concentration decreases again to about 0.4 g P/m^3. The orthophosphate concentration stabilizes at around 0.25 g P/m^3. This indicates that phosphorus removal efficiency has been achieved. Phosphorus removal is accomplished through biological and chemical processes. Orthophosphate is the form directly involved in biological phosphorus removal and is an indicator of biological activity in the system. Oxygen levels play a critical role in phosphorus removal processes. Adequate oxygen levels support nitrification and denitrification processes, while low oxygen levels promote anoxic conditions and can affect phosphorus removal. The initial stability, mid-term fluctuations, and final stability highlight the dynamic nature of wastewater treatment processes. Continuous monitoring and adaptive management are crucial for maintaining optimal performance. To prevent sudden increases in phosphorus concentrations and ensure compliance with regulatory standards, the biological and chemical processes in the system must be continuously monitored. Regular calibration of the simulation model with real-time data will improve prediction accuracy and enhance operational decision-making processes. Investigating the causes of increases in TP can lead to targeted improvements in phosphorus removal processes. In this context, using the SUMO simulation model is a critical tool for enhancing the operational efficiency of the treatment plant and achieving long-term sustainability goals.

Volatile Fatty Acids (VFA) are critical parameters in evaluating the performance and efficiency of wastewater treatment plants. Volatile fatty acids are significant components formed during the biological degradation of organic matter in wastewater and determine the efficiency of treatment processes. The low TP values and stable trend in the simulation results indicate that the facility effectively removes volatile fatty acids and is successful in organic matter removal. In conclusion, the data in this graph show that the facility is effective in total phosphorus removal and complies with

the new EU regulations. Fluctuations should be carefully examined, and long-term monitoring should be ensured to maintain performance continuity. Lowering oxygen levels also leads to a decrease in nitrate concentrations. This reduction in nitrate means that less nitrate is available to enter the anaerobic zones. Therefore, the process of phosphorus removal is impacted, as the availability of nitrate in these anaerobic conditions is crucial. Without sufficient nitrate, the efficiency of phosphorus removal can be significantly reduced, affecting the overall performance of the wastewater treatment system. This interdependence highlights the importance of maintaining optimal oxygen levels to ensure both effective nitrogen and phosphorus removal processes in the treatment plant.
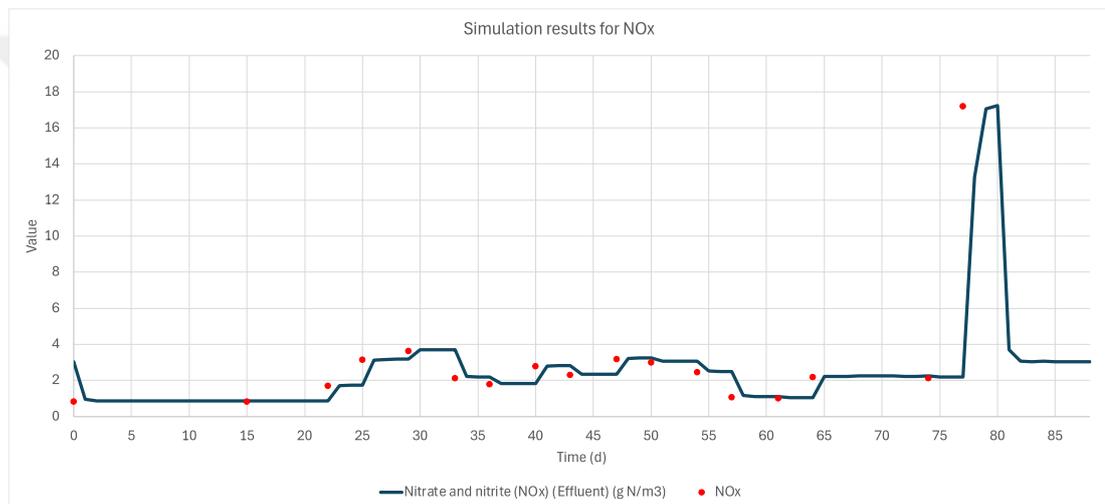
Figure 4.9. Dynamic simulation results - Total NOx (SUMO^{TM}-Dynamita).

Figur 4.9. shows how the concentrations of nitrate and nitrite (NOx) in the effluent change over a period of 88 days. Initially, the NOx concentration is approximately 3 g N/m^3, but from the 2nd day, it drops to around 0.9 g N/m^3 and remains at these levels until day 22, indicating effective denitrification processes. Around day 25, a significant increase in NOx concentration is observed, reaching approximately 4 g N/m^3 by day 30. This increase is attributed to changes in the characteristics of the influent water. Around day 75, another sudden and significant increase in NOx concentration is observed, reaching approximately 17 g N/m3. This could be due to a sudden change in the characteristics of the influent water. From day 80 onwards, the NOx concentration decreases again, stabilizing at around 3 g N/m^3. NOx removal depends on the effectiveness of biological nitrification and denitrification processes, and the balanced management of these processes plays a critical role in controlling NOx levels.

Oxygen levels are an important factor in the effectiveness of nitrification and denitrification processes. The initial stability, mid-term fluctuations, and final stability highlight the dynamic nature of wastewater treatment processes.

By dynamically simulating oxygen levels in SUMO, the optimal conditions for both nitrification and denitrification in a carousel reactor were identified. High oxygen levels promoted nitrification but inhibited denitrification, while low oxygen levels slowed nitrification and reduced nitrate formation. The reactor length was optimized based on the oxygen consumption rate and flow rate. These simulations provided critical insights into the balance needed to ensure effective nitrogen removal while maintaining phosphorus removal efficiency. Adjusting the air output from blowers was key to controlling oxygen levels and optimizing the overall process efficiency. Reducing oxygen levels also reduces nitrate concentrations. This reduction in nitrate leads to less nitrate entering the anaerobic zones, affecting phosphorus removal. In this context, dynamic simulations using the SUMO simulation model show that oxygen levels need to be carefully adjusted, and these adjustments have a critical impact on the treatment efficiency.

5. CONCLUSION AND RECOMMENDATION

In this thesis, a dynamic simulation study was conducted for the studied WWTP to validate the process design concerning effluent quality, wet sludge production, sludge age, and airflow rate. The primary objective was to ensure that the plant operates efficiently within the designed parameters and meets the regulatory discharge limits. The results obtained from the dynamic simulations provided critical insights into the behavior of dissolved oxygen (DO) levels and their impact on the biological processes within the reactors. By adjusting the air supply dynamically, the simulations were able to balance the oxygen levels, which is crucial for maintaining optimal conditions for both nitrification and denitrification. High oxygen levels promoted nitrification, while low oxygen levels were necessary for effective denitrification, demonstrating the delicate balance required in managing DO levels.

Implementing dynamic DO control systems significantly improved energy efficiency by adjusting the air supply based on real-time biological activity in the reactor. The dynamic simulations validated that the studied WWTP could meet the stringent EU discharge limits for COD, TSS, TN, and TP. The results confirmed the plant's operational efficacy and its capability to handle the anticipated loads while achieving the desired effluent quality. The dynamic simulation results also highlighted the importance of maintaining appropriate airflow rates in the aeration basins to support the biological treatment processes. Variations in required airflow rates between different temperatures underscore the need for adaptable operational strategies to ensure consistent treatment performance throughout the year. The plant generally maintained key effluent quality parameters within acceptable ranges, though occasional peaks suggested potential operational challenges. The dynamic simulations provided critical insights into the behavior of dissolved oxygen (DO) levels and their impact on the biological processes within the reactors. By adjusting the air supply dynamically, the simulations were able to balance the oxygen levels, which is crucial for maintaining optimal conditions for both nitrification and denitrification. High oxygen levels promoted nitrification, while low oxygen levels were necessary for effective denitrification, demonstrating the delicate balance required in managing DO

levels. Implementing dynamic DO control systems significantly improved energy efficiency by adjusting the air supply based on real-time biological activity in the reactor. The dynamic simulations validated that the studied WWTP could meet the stringent EU discharge limits. The results confirmed the plant's operational efficacy and its capability to handle the anticipated loads while achieving the desired effluent quality.

Overall, the simulation results confirmed that the studied WWTP is capable of meeting the stringent discharge limits for effluent quality validating the plant's design and operational strategies, and ensuring compliance with environmental standards and effective treatment performance.

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APPENDICES

APPENDIX A: MODEL SET-UP (DYNAMITA-SUMO)

APPENDIX A

Table A. 1. The other fractionations the influent.

Influent Fractions Name	Value	SI unit	US Unit
Fraction of VSS/TSS	70.0	%	%
Fraction of filtered COD (SCCOD, 1.5 µm, incl. colloids) in total COD (TCOD)	40.0	%	%
Fraction of flocculated filtered (SCOD, wo colloids) COD in total COD (TCOD)	24.0	%	%
Fraction of VFA in filtered COD (SCCOD, 1.5 µm, incl. colloids)	25.6	%	%
Fraction of soluble unbiodegradable organics (SU) in filtered COD (SCCOD, 1.5 µm, incl. colloids)	15.0	%	%
Fraction of particulate unbiodegradable organics (XU) in total COD (TCOD)	10.0	%	%
Fraction of heterotrophs (OHO) in total COD	3.0	%	%
Fraction of endogenous products (XE) of OHOs	5.0	%	%
Fraction of colloidal unbiodegradable organics (CU) in colloidal COD (SCCOD-SCOD)	5.0	%	%
Fraction of NHx in total Kjeldahl nitrogen (TKN)	65.0	%	%
Fraction of PO4 in total phosphorus (TP)	65.0	%	%
Fraction of N in readily biodegradable substrate (SB)	4.0	%	%

Key components	mg COD/L	% of total
VFAs	55.0	10.2%
Readily biodegradable substrate (non-VFA)	41.8	7.8%
Colloidal slowly biodegradable substrate	81.8	15.2%
Particulate slowly biodegradable substrate	251.4	46.7%
Soluble unbiodegradable organics	32.3	6.0%
Colloidal unbiodegradable organics	4.3	0.8%
Particulate unbiodegradable organics	53.8	10.0%
Ordinary heterotrophs (OHO)	16.1	3.0%
Endogenous decay products	0.81	0.15%

Key components N	mg N/L	% of total
Ammonia	29.3	65.0%
N in biomass	1.1648	2.6%
N in endogenous decay product	0.0484	0.1%
Soluble biodegradable organic N	1.6736	3.7%
Colloidal biodegradable organic N	0.8178	1.8%
Soluble unbiodegradable organic N	0.3228	0.7%
Colloidal unbiodegradable organic N	0.0430	0.1%
Particulate unbiodegradable organic N	0.5380	1.2%
Particulate biodegradable organic N	11.1416	24.8%
Total TKN	**45.0**	**100.0%**

Key components P	mg P/L	% of total
Phosphate	6.2	65.0%
P in biomass	0.3489	3.6%
Stored polyphosphates	0.1000	1.0%
Soluble biodegradable organic P	0.4184	4.4%
Colloidal biodegradable organic P	0.1636	1.7%
Soluble unbiodegradable organic P	0.0646	0.7%
Colloidal unbiodegradable organic P	0.0086	0.1%
Particulate unbiodegradable organic P	0.0538	0.6%
Particulate biodegradable organic P	2.2021	22.9%
Total P	**9.6**	**100.0%**

Table A. 2. Calculation of air flow rates in carousel for stages.

Symbol	T=12°C	T=25°C	Unit
Ring1- Air Flow	17900	18400	m^3/d at NTP
Ring2- Air Flow	17837	18350	m^3/d at NTP
Ring3- Air Flow	17366	18100	m^3/d at NTP
Total	**53103**	**54750**	**m^3/d at NTP**
Symbol	T=12°C	T=25°C	Unit
Ring1- Air Flow	20480	21200	m^3/d at NTP
Ring2- Air Flow	20445	21150	m^3/d at NTP
Ring3- Air Flow	20200	21000	m^3/d at NTP
TOTAL	**60926**	**63350**	**m^3/d at NTP**

Table A. 3. Mass loading calculation results for studied WWTP (STAGE-1).

Symbol	Influent	Clarifier Sludge	Clarifier Effluent	Discfilter Effluent	Thickening Effluent	Dewatering Effluent	Unit
Flow rate	11132	7792.4	11622	11122	30.6	278.7	m^3/d
Total chemical oxygen demand	5755	41316	418.3	357.0	79.9	127.8	kg/d
Total suspended solids (TSS)	2957	58753	66.2	1.3	123.9	186.5	kg/d
Total nitrogen	478.7	1856.4	39.7	36.0	3.5	6.0	kg/d
Total phosphorus	95.7	1998.1	20.4	17.4	4.5	6.9	kg/d
Orthophosphate (PO_4)	62.2	11.5	17.2	16.5	0.0	0.3	kg/d
Total BOD_5	2903	8385.0	19.5	9.8	13.9	21.2	kg/d

Table A. 4. Mass loading calculation results for studied WWTP (STAGE-2).

Symbol	Influent	Clarifier Sludge	Clarifier Effluent	Discfilter Effluent	Thickening Effluent	Dewatering Effluent	Unit
Flow rate	12177	8523.9	12665.5	12165.5	36.4	350.8	m^3/d
Total chemical oxygen demand	6551.2	45469	474.8	405.5	98.1	157.6	kg/d
Total suspended solids (TSS)	3365.6	64460.9	76.8	1.5	147.5	222.1	kg/d
Total nitrogen	548.0	2056.4	50.3	46.0	4.4	7.7	kg/d
Total phosphorus	116.9	2188.3	30.6	27.0	5.2	8.4	kg/d
Orthophosphate (PO_4)	76.0	18.1	27.0	25.9	0.1	0.5	kg/d
Total BOD_5	3304.6	9342.0	21.8	10.5	18.7	28.4	kg/d

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