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MASTER’s Degree in Chemical Engineering and Sustainable Processes

MASTER’s Degree thesis

Upgrading Wastewater Treatment plants for Nutrients Removal:

Possible strategies for the most relevant situations in the Portuguese context

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ABBREVIATIONS:

AGS-Aerobic Granular Sludge

ALE- Alginate Like Exopolymer

ANAMMOX-Anaerobic Ammonium Oxidizer

AOB-Ammonia Oxidizing Bacteria

ARP-Activated Return sludge Process

BOD-Biochemical Oxigen Demand

BNR – Biological Nutrients Removal

CEPT – Chemically Enhanced Primary Treatment

CIP-Cleaning In Place

COD-Chemical Oxigen Demand

CSOs-Combined Sewer Overflows

DN - Denitriphication

DO – Dissolved Oxygen

EBPR – Enhanced Biological Phosphorous Removal

EDCs-Endocrine Disrupting Compounds

EEA-European Environment Agency

EPS-Extra Polymeric Substances

GAOs - Glycogen Accumulating Organisms

HRT – Hydraulic Retention Time

IFAS-Integrated Fixed film Activated Sludge

LMH-Liters of filtered water/m2 of surface area/hour of filtration time

MABR-Membrane Aerated BioReactor

MBBR-Moving Bed BioReactor

MBR-Membrane BioReactor

MF-Micro Filtration

MLE – Modified Ludzac Ettinger

MLSS - Mixed Liquor Suspended Solids

ML(VSS) - Mixed Liquor Volatile Suspend Solids

(N)IR – (Nitrates) Internal Recycle

OHOs – Ordinary Heterotroph Organisms

OTE-Oxygen Transfer Efficiency

PAOs - Phosphorous Accumulating Organisms

PHA - PolyHydroxyAlkanoates

PN-Partial Nitritation

RAS – Recycled Activated Sludges

SAD-Specific Aeration Demand

SADp-Specific Aeration Demand per permeate

SBR-Sequencing Batch Reactor

SLR-Surface Loading Rate

SND- Simultaneous Nitrification Denitrification

SOR-Surface Overflow Rate

SRT – Sludge Retention Time

SVI-Sludge Volume Index

TKN-Total Kjeldhal Nitrogen

TMP-Trans Membrane Pressure

TSS – Total Suspend Solids

UASB – Upflow Anaerobic Sludge Blanket

UCT – University of Cape Town

UF-Ultra Filtration

UWWTD-Urban Wastewater Treatment Directive

VFAs – Volatile Fatty Acids

VIP – Virginia Initiative Plant

WAS – Wasted Activated Sludge

WISE-Water Information System Europe

WWTP – WasteWater Treatment Plant

Abstract:

UWWTD revision in 2024 established more stringent limits on nutrients removal for UWWTPs. Out of the 529 Portuguese WWTPs present in EU 2022 dataset, 108 must be retrofitted to adapt to the new EU standards. Of these 108 WWTPs, 68, with a nominal treatment capacity corresponding to 55% of the national one, either lack a secondary treatment step, or possess it in the form of a continuous suspended biomass system. Denmark model, globally recognised as a benchmark in the wastewater field, was studied to find a possible retrofitting strategy for these 68 Portuguese WWTPs. A2/O continuous suspended biomass reactors or A/O ones coupled with chemical P precipitation revealed to be at the core of top performing Danish WWTPs. A qualitative review of the main factors playing a major role in determining the feasibility of the Danish model in the Portuguese context was performed. Possible alternative solutions for those Portuguese WWTPs not fulfilling the requirements to adopt Danish model were rapidly screened. A first comparison of the order of magnitude of the possible performance changes after the upgrade interventions and of investments required for the retrofit interventions was obtained through a web review. Maximisation of existing infrastructure and of the role of biological processes in nutrients removal was found to be the most cost effective solution to upgrade existing WWTPs (0,008-0,14 euros/m3 treated) with specific investments considerably lower than implementing advanced technologies such as IFAS, MBR, AGS, MABR or rebuilding the WWTP (0,12-0,94 euros/m3 treated) and (0,11-1,58 euros/m3 treated) respectively. The questionable trustability of the available data however, forces the reader to use the data presented only as preliminary guesses. Access to relevant datasets will be essential to build a more structured review in the future

Abstract in Italiano:

La revisione di fine 2024 della direttiva UE 91/271 ha introdotto limiti più stringenti per la rimozione dei nutrienti negli impianti di trattamento acque reflue. Dei 529 impianti portoghesi riportati nel database europeo del 2022, 108 devono essere adeguati ai nuovi standard europei. Di questi 108, 68, con una capacità nominale di trattamento pari al 55% della nazionale, o non dispongono di un trattamento secondario, o lo hanno sottoforma di un reattore continuo a biomassa sospesa. Il modello danese, globalmente riconosciuto come esempio nel campo delle acque reflue, è stato studiato al fine di trovare una possibile strategia di adeguamento per questi 68 impianti portoghesi. Al centro del sistema di trattamento dei migliori impianti danesi si è rivelato esserci un bioreattore a più zone (anaerobica/anossica/ossica) eventualmente dotato di precipitazione chimica del Fosforo. Una valutazione qualitativa dei fattori principali per determinare la fattibilità di una esportazione del modello danese nel contesto portoghese è stata svolta. Soluzioni alternative per quegli impianti non adatti a implementare il modello danese sono state poi rapidamente vagliate. Infine, un primo confronto degli ordini di grandezza delle possibili prestazioni post adeguamento e degli investimenti richiesti per attuare l'adeguamento è stato ottenuto tramite una ricerca sul web. La massimizzazione dell'utilizzo delle infrastrutture esistenti e dei processi biologici si è rivelata essere la miglior soluzione d'adeguamento per gli impianti esistenti in termini di rapporto costi/benefici (0,008-0,14 euros/m3 trattato) con costi specifici d'investimento considervolmente minori di quelli per l'introduzione di tecnologie avanzate come IFAS, MBR, AGS, MABR (0,12-0,94 euros/m3 treated) o di quelli di ricostruzione da zero dell'impianto (0,11-1,58 euros/m3 treated). La dubbia affidabilità delle fonti di data costringe tuttavia il lettore a considerare i risultati solo come stime preliminari. L'accesso a database più strutturati sarà essenziale per svolgere valutazioni più complete in futuro.

1 Introduction

1.1 Motivation and Problem Statement

Water is the basis of life. Humans, like all other animals, plants and living beings, need to access water with specific physical, chemical, and microbiological characteristics. (*NASA-a*, no date)

Water is changed by what it gets in contact with. Natural water cycle is supposed to guarantee that water gains back the characteristics that enable the possibility of having life on earth. (*NASA-b*, no date)

Human society obviously relies on water. It has always been like that. What is not obvious is how profoundly water gets changed by the meeting with sedentary human society. The effects of our human society impact on water are so impressive that a word has been coined to describe what water transforms into after we use it: wastewater.

Since ancient Egypt times systems to treat wastewater replicating natural cycles have existed. (Gardner, 2021) In modern days society however water gets altered by direct or indirect contact with humans in such a deep way that the natural cycle on its own is not sufficient anymore to transform wastewater back into water again.

The natural water cycle must be engineered to treat modern wastewater. The original inspired-by-nature treatment systems have in fact evolved through centuries and are now referred to as Natural Based Solutions (NBS). (Noor et al., 2025)

NBS however often reveal not to be the most effective options in terms of time and space efficiency. This is why humans invented wastewater treatment plants (WWTPs). The original goal of WWTPs was one. Treat wastewater collected by sewer systems before releasing it back into the ecosystem to alleviate the environment as much as possible from wastewater purification burden.

Most advanced WWTPs are mainly structured on five levels of treatment:

- -preliminary: aims at removing large debris and solid particles (Noor et al., 2025)
- -primary: aims at removing sands, greases, oils and organic compounds dissolved (Noor et al., 2025)
- -secondary: aims at completing the removal of soluble organic compounds (Noor et al., 2025)
- -more stringent-tertiary: aims at removing pathogens and nutrients, which are Nitrogen-formed and Phosphorous-formed compounds (Noor et al., 2025)
- -quaternary: aims at removing micropollutants and contaminants of emerging concern such as microplastics, pharmaceuticals, synthetic hormones, pesticides, personal care products, antibiotic resistant genes, etc to enhance the possibility of treated water reuse (Jurik et al., 2024)

The fifth level, the quaternary step, it’s relatively new. By 2045 big WWTPs will have to adopt it.

However data on WWTPs implementing quaternary step is still almost always missing. (*Revised urban wastewater treatment directive*, 2024)

Cleary not all WWTPs are constituted of the totality of these five levels. Europe countries are worldwide among the most complete ones, achieving almost always complete preliminary, primary and secondary level and frequently possessing also the tertiary one. To understand the importance of the tertiary step one must first perceive the impact of WWTPs discharging nutrients rich waters.

Nitrogen and Phosphorous are in various compounds commonly present in wastewaters. These compounds represent a rich source of food for plants and algae. This is the reason they are usually referred to as nutrients. Nutrients, if not adequately removed before discharge, may cause excessive growth of algae in the receiving water bodies. Algae can rapidly deplete the oxygen levels and bring to death the aquatic ecosystem. This phenomenon is called eutrophication. *(United Nations Environment Program (UNEP)*, no date)

Besides that, the additional dissolved organic matter originating from dead algae, influences the pH and redox potential of the eutrophic waters impacting heavy metals mobility and toxicity levels. (Cui et al., 2025)

Wastewater usually represents about 25% of the total pollution load that reaches the seas from Europe in terms of N, and about 50% in terms of P (Pistocchi et al., 2021)

Point source emissions from UWWTPs can represent an important share of nutrient load in surface waters. Particularly in regions that are densely populated or where the wastewater treatment level is still inadequate. The contribution of point sources from UWWTPs discharges to the total load in surface water is more important for P than for N, since a large part of total N load originates from diffuse agricultural sources (Grizzetti et al., 2021 as cited in Pistocchi et al., 2023)

These facts confirm that the barrier function of WWTPs is essential to protect water bodies from eutrophication.

Modern WWTPs in proper operation usually remove more than 90% of total P and 80% of total N, with a potential to reach a removal close to 90% for N and above 95% for P in the best cases according to DWA, 2020 (as cited in Pistocchi et al., 2023)

Table 1-1: Assumed nutrients removal performances by level of treatment (Pistocchi et al., 2023)

Assumed Nutrients % removal steps efficiency	N	P
Mechanical primary treatment	25	30
mechanical + biological secondary treatment	55	60
tertiary/more stringent treatment	80	90

From Table 1-1 it is evident the importance to adopt efficient tertiary step to tackle nutrients discharges. Modern tertiary step configurations nutrients percentage removal cannot be improved substantially. The tertiary processes available today already reach very high levels.

They are typically based on anoxic-oxic (A/O) zones in the biological tank for N removal coupled with chemical P precipitation through metal salts, or on anaerobic-anoxic-oxic zones in the biological tank (A2/O). (*Environmental Protection Agency, (EPA), 2022*)

Despite the high performances of tertiary steps Europe still isn't out of eutrophication risk. (Table 2-6) Many WWTPs in fact still lack a tertiary nutrients removal step.

This work will try to suggest ways of optimising existing tertiary treatment steps, and introducing efficient tertiary steps in WWTPs missing it entirely, focusing on the Portuguese context.

It is worth mentioning that, even if ideally all required WWTPs adopted optimized nutrients removal tertiary steps, it could still be insufficient to meet the revised UWWTD goals if not accompanied by structural changes to our livestock and agricultural industrial system. (Grizzetti et al., 2021)

However, in cases where WWTPs lack the required nutrients removal units, great benefits for EU waters would come from their introduction.

1.2 Objectives of the thesis

- Group Portuguese WWTPs in macrofamilies according to design size capacity, level of treatment achieved and N and P removal steps present. (chapter 4)
- Characterization of the different macrofamilies of Portuguese WWTPs that require by law to be retrofitted in terms of nutrients removal. (chapter 4)
- Creation of a priority list for the macrofamilies of WWTPs that must be retrofitted excluding some based on low share of national design capacity and high starting level of treatment achieved. (chapter 5)
- Creation of subgroups of Portuguese WWTPs among the priority ones based on shared waterline sequences in terms of primary step and type of biological reactor. (chapter 5)
- Identification of the most common starting configurations for the priority Portuguese WWTPs to retrofit and evaluation of their average performances. (chapter 5)
- Identification of reference Danish WWTPs for what concerns nutrients removal performances and evaluation of their performances (chapter 6)
- Comparison of performances between Danish reference WWTPs and selected Portuguese WWTPs possessing common configurations and needing retrofit. (chapter 6)
- Overview of the factors that determine the feasibility of a retrofit of the most common priority Portuguese starting situations on the Danish reference WWTPs examples. (chapter 7)
- First guess of the order of magnitude of the investments required to perform a retrofit based on the Danish example. (chapter 7)
- Overview of complementary/alternative strategies to continuous suspended biomass systems to achieve nutrients removal and estimate of the investments required to follow these paths. (chapter 8)

1.3 Structure of the Thesis

- A general introduction of the law framework and of the European context will be given in chapter 2. A special focus will be reserved for Portugal and Denmark. The first being the country object of the study, the second being chosen as the model to aspire to.
- A presentation of the methodology followed during the information research and the data analysis is addressed in chapter 3.
- Analysis of Portugal WWTPs compliance with respect to the revised Directive is object of chapter 4, while identification of the most critical target subgroup of Portuguese WWTPs to retrofit is what chapter 5 deals with.
- Identification of reference Danish WWTPs to be taken as a model for nutrients removal and comparison of their performances with those of the WWTPs belonging to the Portuguese priority list is object of chapter 6.

- Overview of the key factors determining the feasibility of the introduction of the Danish model in the Portuguese context is addressed in chapter 7.
- Overview of the possible alternative or complementary solutions to the Danish model to retrofit Portuguese WWTPs is addressed in chapter 8.

2 Regulatory and Environmental Context of Nutrient Removal

2.1 European Regulatory Framework

Nowadays EU asks to its member states to engage to protect actively the environment by requiring their internal policies to follow the general guidelines provided in the European Green Deal (EGD, 2019).

Wastewater collection and treatment obviously play a major role in environment protection.

EU regulated it for the first time in 1991, publishing the *Council Directive of 21 May 1991 concerning urban wastewater treatment (Urban wastewater treatment directive (UWWTD),1991)* whose aim was to shape member states policies in terms of wastewater management.

Until year 2000 EU had separate laws and directives for each sector of water management. Ground waters were dealt separately from surface ones, drinking ones separately from wastewaters and bathing waters on their own.

In 2000, EU unified these areas under the umbrella of the *Water framework directive (WFD): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.*

Some of the directives managing these areas were completely englobed in the WFD. Others, such as the *Directive on drinking water quality 98/83,* and the *Urban wastewater treatment Directive 91/271,* continued to be valid, but their goals were included in WFD ones. (*Water Framework Directive (WFD), 2000)*

At the end of 2024, also due to the ambitious goals set in EGD, a revised version of the UWWTD was published (*Revised urban wastewater treatment directive*, 2024). In the revised version of the UWWTD many targets were modified and some new ones were introduced. It would be out of the scope of this work to mention them all but a list of some key families of new or modified targets is given. In the next two decades member states will have to shape their internal policies on all topics related to wastewater according to the following objectives:

- 1-extension of the raw sewage collecting network
- 2-better management of storm waters
- 3-Improvement of the WWTPs pollutants removal performances
- 4-Improvement of the WWTPs operative efficiency

Figure 2.1 Figure 2.2 and Figure 2.3 give some of the reasons behind objective 1, 2 and 3. Objective 4 is together with number 2 the one that has assumed more importance recently. It mainly implies the reduction of chemicals and energy consumption in WWTPs operation and shifting of the paradigm from a resource consuming reality to water resource recovery facility (WRRF).

Objective 3 has at least 2 main sub-tasks: nutrients removal increase and micropollutants and contaminants of emerging concern removal increase. As already mentioned the core of this work will consider only nutrients removal increase.

Discharges of waste water from unconnected dwellings contribute significantly to less than good water quality in:

- 8.3% of river water bodies
- 6.6% of lake water bodies
- 4.4% of transitional water bodies
- 14.8% of coastal water bodies
- 11.3% of groundwater body area

Figure 2.1: Impacts on EU waters due to incomplete extension of the collecting system (WISE,2025)

Discharges of storm water overflows contribute significantly to less than good water quality in:

- 4.4% of river water bodies
- 0.8% of lake water bodies
- 5.4% of transitional water bodies
- 2.7% of coastal water bodies
- 0.4% of groundwater body area

Figure 2.2: Impacts on EU waters due to inadequate management of storm waters (WISE,2025)

- Discharges of urban waste water contribute significantly to less than good water quality in:
  - 13.3% of river water bodies
  - 4.0% of lake water bodies
  - 23.4% of transitional water bodies
  - 22.2% of coastal water bodies
  - 2.8% of groundwater body area

Figure 2.3: Impacts on EU waters due to inadequate wastewater treatment (WISE,2025)

To tackle nutrients loads discharged by WWTPs with treated effluents, the revised UWWTD has set new goals. A comparison with the previous ones should facilitate the reader in the understanding of the order of magnitude of the changes requested.

In the original 1991 UWWTD, from which Table 2-1: EU Council Directive of May 1991, UWWTD, Nutrients removal expected performances (Council Directive of May 1991, urban wastewater treatment directive,1991) is extracted, nutrients removal units, referred to as more stringent treatment, (more stringent than secondary) were required only for WWTPs discharging in eutrophication-sensitive areas with a capacity above 10 000 pe.

In the revised UWWTD, from which Table 2-2 is taken, the performance requirements are made more stringent and extended to more plants. Now every WWTP with size above 150 000 pe is asked to comply with them irrespective of the discharge zone classification. Treatment plants with capacity between 10 000 and 150 000 pe must adequate only if discharging in sensitive areas instead.

Table 2-1: EU Council Directive of May 1991, UWWTD, Nutrients removal expected performances (Council Directive of May 1991, urban wastewater treatment directive,1991)

1991 UWWTD Nutrients removal target performances	P	N
effluent limit concentration (mg/L) for WWTPs above 100 000 pe discharging in eutrophication-sensitive areas	1	10
effluent limit concentration (mg/L) for WWTPs between 10 000 and 100 000 pe discharging in eutrophication-sensitive areas	2	15
Minimum % removal for WWTPs above 100 000 pe discharging in eutrophication-sensitive areas	80	80
Minimum % removal for WWTPs between 10 000 and 100 000 pe discharging in eutrophication-sensitive areas	80	70

Table 2-2: EU revised UWWTD, Nutrients removal expected performances (Revised urban wastewater treatment directive, 2024)

2024 revised UWWTD Nutrients removal target performances	P	N
effluent limit concentration (mg/L) for WWTPs above 150 000 pe	0,5	8
effluent limit concentration (mg/L) for WWTPs between 10 000 and 150 000 pe discharging in eutrophication-sensitive areas	0,7	10
Minimum % removal for WWTPs above 150 000 pe	90	80
Minimum % removal for WWTPs between 10 000 and 150 000 pe discharging in eutrophication-sensitive areas	87,5	80

2.2 European Wastewater Treatment Context

In Table 2-3 we can see European WWTPs divided by level of treatment achieved.

Table 2-3: EU WWTPs divided by level of treatment achieved (WISE,2025)

EU WWTPs divided by level of treatment achieved		% of total
Number of WWTPs achieving primary level	320	1,6
Number of WWTPs achieving secondary level	4423	22,0
Number of WWTPs achieving more stringent level with nutrients removal	15357	76,4
Total	20100	

Table 2-4: EU targets for wastewater collection and treatment (WISE,2025)

EU targets in terms of loads to treat measured in million pe		% of total
Load generated	538,4	
Load to collect	538,4	100
Load to treat achieving secondary level	523	97
Load to treat achieving more stringent level with nutrients removal	360,7	67

Table 2-5: EU distance to wastewater collection and treatment targets (WISE,2025)

EU distance to targets in terms of loads to treat	in million pe	% of total
Load still to collect	12,22	2,3
Load still to treat achieving secondary level	47,45	9
Load still to treat achieving more stringent level with nutrients removal	26,83	5

As a whole EU is not far from achieving the targets self-imposed, (Table 2-5).

The collection task seems to be almost completed. Improving the level of treatment wastewaters are submitted to involves a low but still not negligible share of the total load.

Generally EU states have an high compliance rate with the directive, as visible in Figure 2.4. Among the best ones Denmark (DK), Austria (AT), Germany (DE), Luxembourg (LU) and Sweden (SE) lead.

Portugal (PT), even though achieving an 82% of compliance rate, above EU average of 75,9%, finds himself in the lower half of the table. Spain (ES) achieves a slightly better result. Italy, country sharing some similarities with the Iberic ones, ranks in the last positions with less than 60% compliance rate.

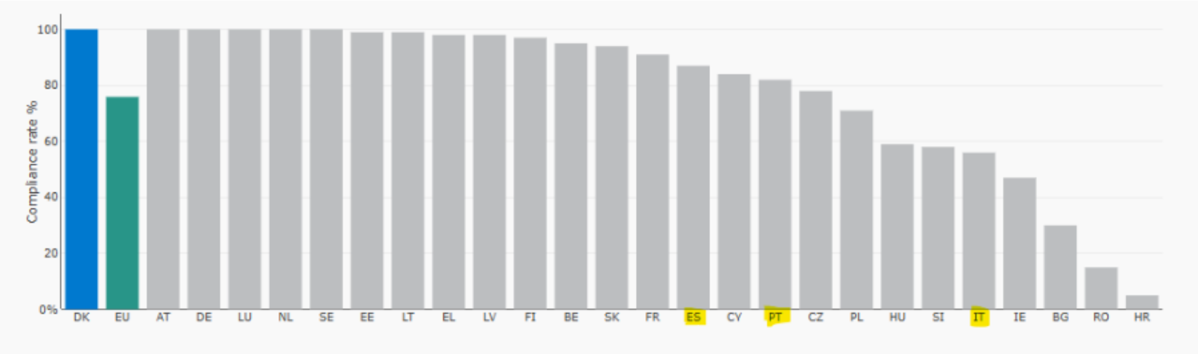


Figure 2.4: EU member states ranking in terms of compliance rate to UWWTD (WISE,2025)

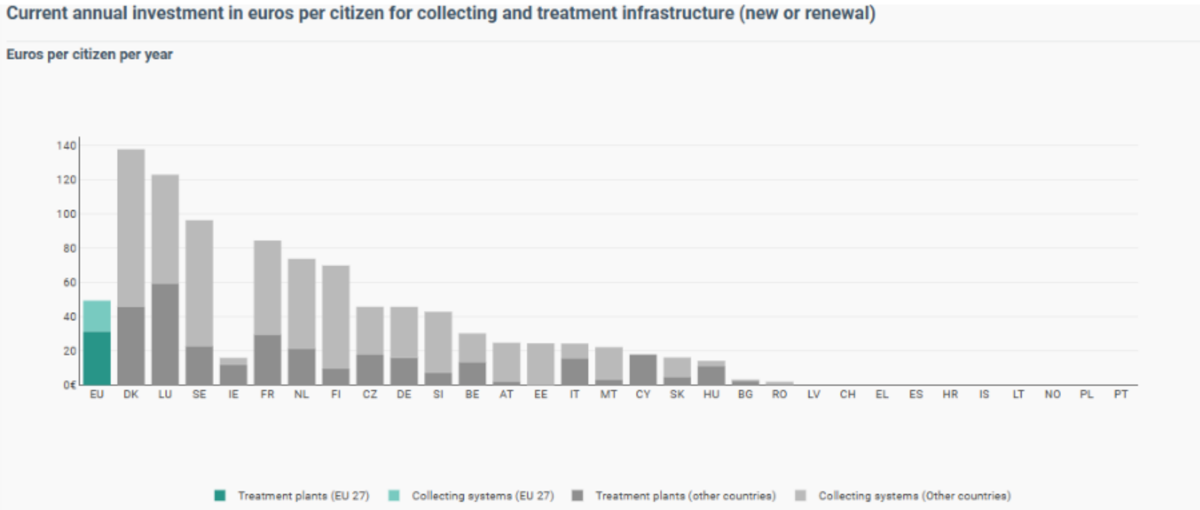


Figure 2.5: EU member states investments comparison for wastewater collection and treatment infrastructure (WISE,2025)

As displayed in Figure 2.5 Denmark, Luxembourg and Sweden reveal to be the countries most willing to invest on wastewater collection and treatment system, with per capita values far above the EU average of 49,4 eur/pe*y.

Denmark ranks first with 137,9 eur/pe*y. Of this 137,9 eur/pe*y an outstanding 92 eur/pe*y are devoted to collection systems improvement.

Portugal, as Spain, has not declared the amount invested. Italy ranks again in the lower part of the table with 24,4 eur/pe*y.

In Figure 2.6 a classification of EU areas according to eutrophication risk is given. Most of Europe WWTPs discharge zones are considered nutrients sensitive. Portugal, together with Greece, Italy, Ireland and parts of Spain, Croatia and France is an exception.

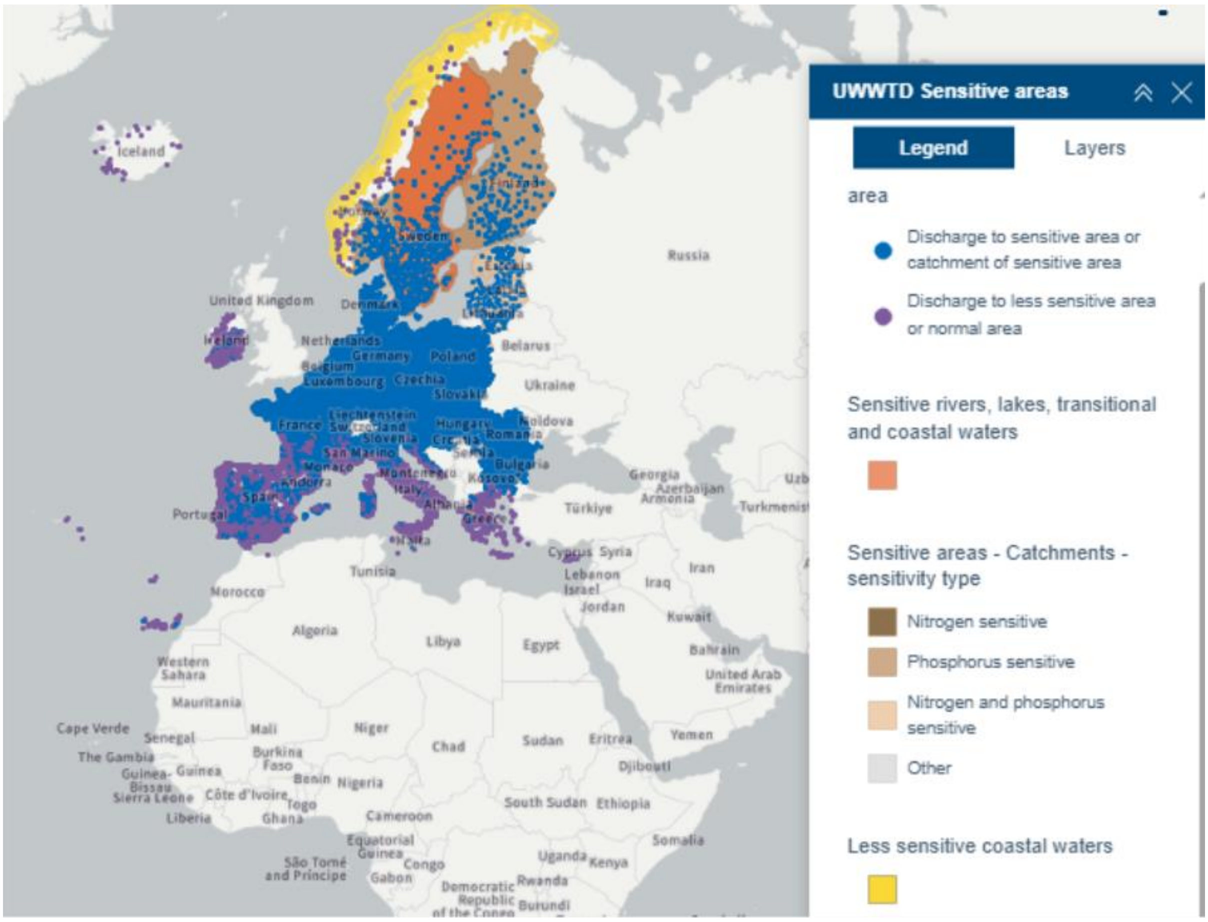


Figure 2.6: EU nutrients sensitive areas classification (WISE,2025)

For what concerns EU water bodies health status Table 2-6 and Table 2-7 give a general picture.

Despite the good starting point of EU wastewater collection and treating system, showed in Table 2-5, EU waters are not in optimal state. Less than half of them don't suffer from any relevant kind of pollution. It is evident that at least three of the main threats to EU water bodies come from categories of pollutants WWTPs should deal with.

Nutrients, chemicals and organic substances represent a substantial share of the causes of EU waters dangerous situation.

Table 2-6: EU endangered surface waters (WISE,2025)

EU endangered surface waters classification	
% of surface waters suffering nutrients pollution	30,6
% of surface waters suffering organic pollution	15,8
% of surface waters suffering chemical pollution	59,3
% of surface waters in danger due to morphological changes	43,6
% of surface waters in danger due to hydrological changes	20,2

Table 2-7: EU endangered ground waters (WISE,2025)

EU endangered ground waters classification	
% of ground waters suffering nutrients pollution	17,4
% of ground waters suffering chemical pollution	25,3
% of ground waters with low water table	14,1

The apparent contrast between Table 2-5 and Table 2-6 and Table 2-7 arises from the categorization strategy EU adopts to define the distance to the imposed targets.

Treatment performances expected from WWTPs achieving a certain level of treatment might be insufficient to guarantee EU waters health. So, even if almost all WWTPs get to thei r design level of treatment, EU waters status can still be quite unsatisfying.

Together with extending the number of WWTPs that achieve the target level of treatment there's a need to redefine the target performances for each level making them more demanding.

This update of the target performances expected by each level of treatment was in fact one of the drivers for urban wastewater treatment directive revision.

2.3 Portuguese Wastewater treatment context

Table 2-8: Portugal EU set targets for wastewater collection and treatment (WISE,2025)

Portugal EU set targets in terms of loads to treat	in million pe	% of total
Load generated	13	
Load to collect	13	100
Load to treat achieving secondary level	11,9	92
Load to treat achieving more stringent level with nutrients removal	1,7	13

Table 2-9: Portugal distance from EU set targets for wastewater collection and treatment (WISE,2025)

Portugal distance from EU set targets in terms of loads	in million pe	% of total
Load still to collect	0	0
Load still to treat achieving secondary level	1,15	9
Load still to treat achieving more stringent level with nutrients removal	0,37	3

As shown in Table 2-8 and Table 2-9 Portuguese WWTPs are not designed to target nutrients removal. This is mainly because Portuguese areas aren't labelled as nutrients sensitive. (Figure 2.7) The main driver for WWTPs retrofits is law obligation.

Since until 2025 only WWTPs discharging in nutrients sensitive areas needed to have nutrients removal units, (Table 2-1: EU Council Directive of May 1991, UWWTD, Nutrients removal expected performances (Council Directive of May 1991, urban wastewater treatment directive,1991) , most of Portuguese WWTPs don't possess one.

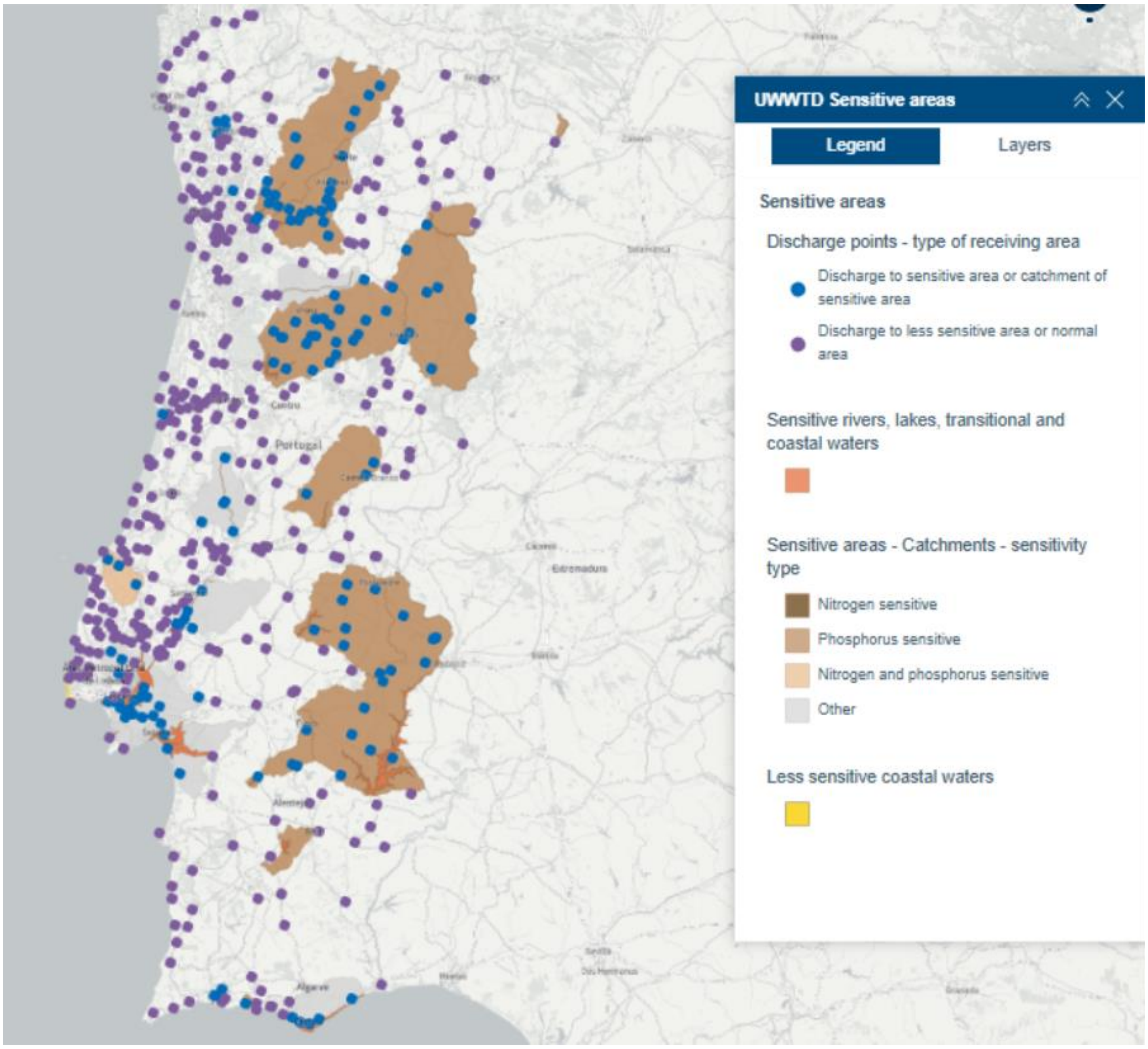


Figure 2.7: Portugal nutrients sensitive areas classification (WISE,2025)

The fact that Portuguese areas aren't labelled as nutrients sensitive, Figure 2.7 doesn't mean that they could fastly become it, especially when considering the poor WWTPs performances. Through Table 2-10, Table 2-11, Table 2-12, Table 2-13 and Table 2-14 a general picture of Portuguese water bodies health status is given. Portugal waters are in good conditions but risk to rapidly lose this status also due to nutrients, chemicals and organic substances loads. These loads should be addressed by efficient WWTPs.

Table 2-10: Portugal surface waters ecological status (WISE,2025)

Portugal surface waters ecological status	
% of waters in bad ecological status	5
% of waters in poor ecological status	12
% of waters in moderate ecological status	33
% of waters in good ecological status	43
% of waters in high ecological status	3
% of waters in unknown ecological status	4

Table 2-11: Portugal surface waters chemical status (WISE,2025)

Portugal surface waters chemical status	
% of surface waters with not good chemical status	8
% of surface waters with good chemical status	67
% of surface waters with unknown chemical status	26

Table 2-12: Portugal ground waters chemical status (WISE,2025)

Portugal ground waters chemical status	
% of surface waters with not good chemical status	23,5
% of surface waters with good chemical status	76,5
% of surface waters with unknown chemical status	0

Table 2-13: Portugal endangered surface waters (WISE,2025)

Portugal endangered surface waters classification	
% of surface waters suffering nutrients pollution	38,1
% of surface waters suffering organic pollution	16,5
% of surface waters suffering chemical pollution	15,2
% of surface waters not in danger of pollution	34
% of surface waters whose danger status is unknown	15,8

Table 2-14: Portugal endangered ground waters (WISE,2025)

Portugal endangered ground waters classification	
% of ground waters suffering nutrients pollution	76,5
% of ground waters suffering chemical pollution	46,7
% of ground waters with low water table	87,3

2.4 Danish Wastewater treatment context

This work will look at Denmark as a reference example to guide the strategy to improve Portugal's nutrients removal strategy. Denmark system should be studied as a whole, starting from wastewaters collection and ending with the sludges management to recover energy and resources. However, since the focus of the thesis will be suggesting strategies to retrofit Portuguese WWTPs to improve their nutrients removal performances, the collection system and the sludge line will be overlooked, knowing however their capital relevance when looking at the system as a whole.

The reasons behind Denmark choice as a reference should already be clear when looking at Figure 2.4 and Figure 2.5, however further clues will be given in Table 2-15 and Table 2-16.

Table 2-15: Denmark EU set targets for wastewater collection and treatment (WISE,2025)

Denmark EU set targets in terms of loads to treat measured in million pe		% of total
Load generated	12	
Load to collect	12	100
Load to treat achieving secondary level	11,8	98,3
Load to treat achieving more stringent level with nutrients removal	10,8	90

Table 2-16: Denmark distance from EU set targets for wastewater collection and treatment (WISE,2025)

Denmark distance from EU set targets in terms of loads measured in million pe		% of total
Load still to collect	0	0
Load still to treat achieving secondary level	0,01	0,1
Load still to treat achieving more stringent level with nutrients removal	0,03	0,3

Denmark has the vast majority of its WWTPs already designed for nutrients removal. Differently from Portugal, whose areas are mainly regarded as less sensitive or normal areas, Denmark is labelled as a sensitive discharge area. (Figure 2.8) This might be a driver for the high share of WWTPs adopting nutrients removal units.

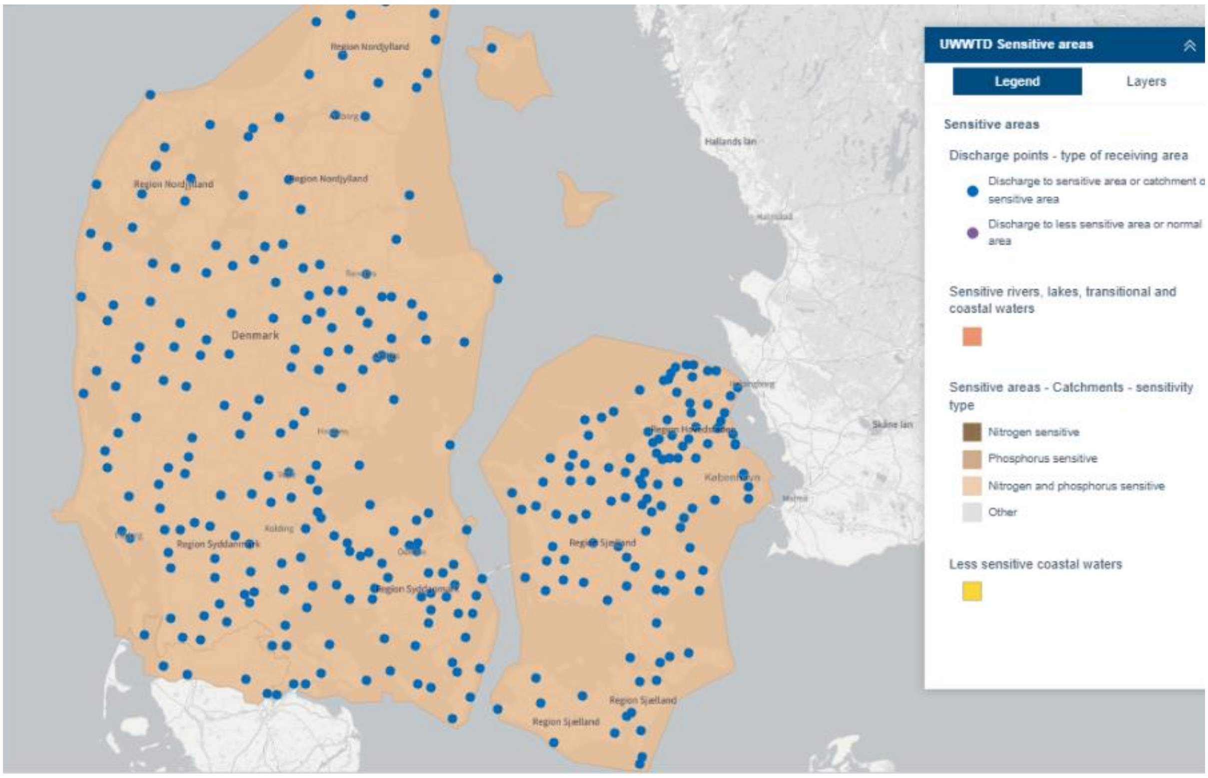


Figure 2.8: Denmark nutrients sensitive areas classification (WISE,2025)

Table 2-17: Denmark endangered surface waters (WISE,2025)

Denmark endangered surface waters classification	
% of surface waters suffering nutrients pollution	9,1
% of surface waters suffering organic pollution	5,5
% of surface waters suffering chemical pollution	6,3
% of surface waters in danger due to morphological changes	36,1
% of surface waters whose danger status is unknown	55,4

Table 2-18: Denmark endangered ground waters (WISE,2025)

Denmark endangered ground waters classification	
% of ground waters suffering nutrients pollution	17,2
% of ground waters suffering chemical pollution	49,4
% of ground waters with low water table	7,5

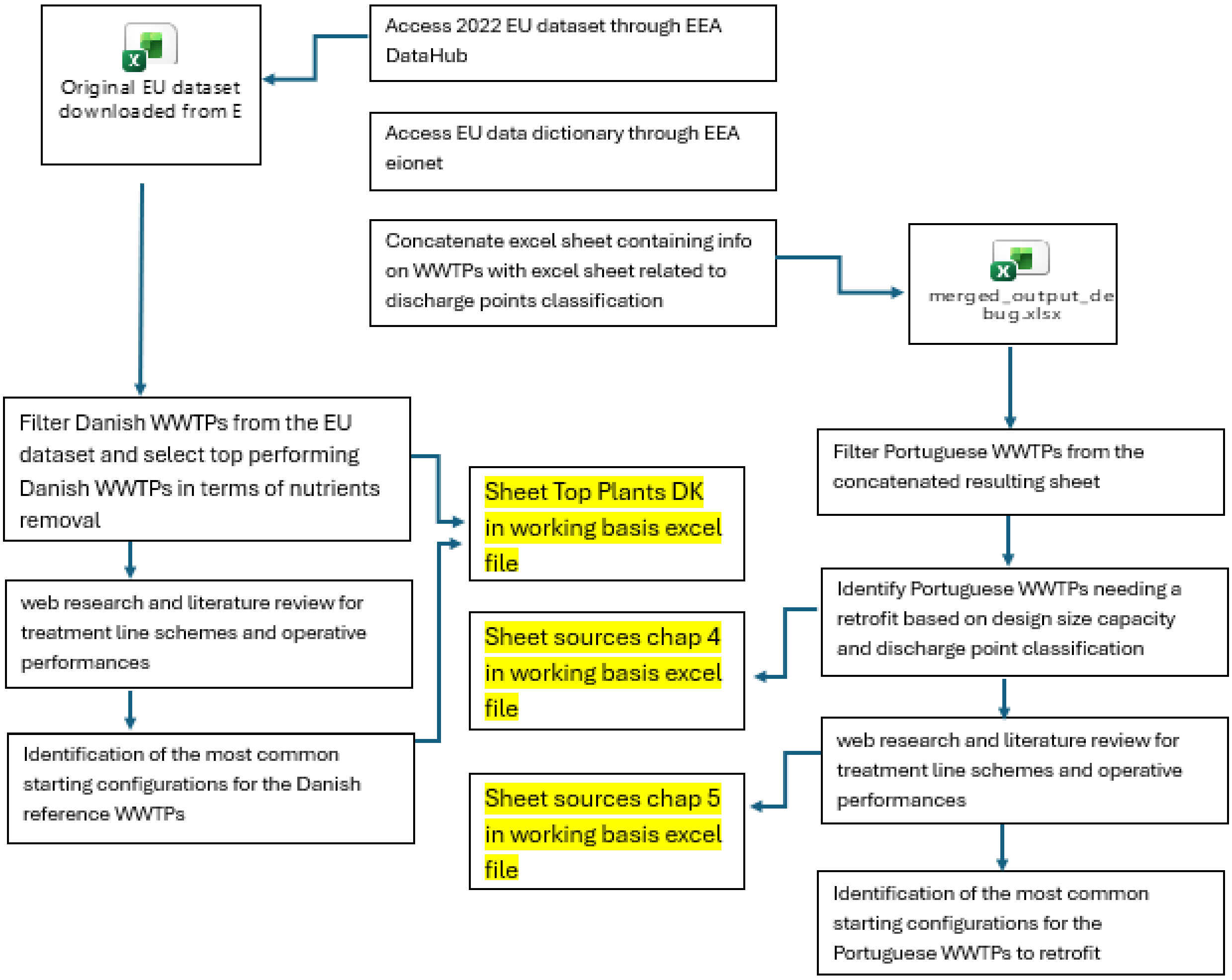
As clearly visible in

Table 2-17 and Table 2-18
Denmark waters suffer considerably less than Portuguese ones of nutrients discharge loads. This is a positive effect of the Danish system. The comparison between Denmark and Portugal water bodies health allows to understand that WWTPs function is essential in determining water bodies well-being. Excluding the large share of superficial waters whose status is unknown,
the Danish system protects sensitive-labelled areas that result less in danger in terms of nutrients pollution than the non-sensitive labelled Portuguese ones, not protected by the Portuguese system.

3 Methodology and Data Sources

3.1 Overview of Methodological Approach

An overview of the methodological approach is given. Excel sheets are available as supplementary material.



After these steps were implemented, a web research and literature review of the factors affecting Danish reference model implementation in the Portuguese context of interest was performed

Then a web research and literature review of different technologies with respect to those representing the core of the Danish reference model was performed to find alternative/complementary solutions for Portuguese WWTPs of interest not fulfilling the requirements to rely only on the Danish model.

Finally a web research and literature review of some retrofitting case studies and greenfield works both in terms of performances achieved and investments required was performed.

3.2 Data Sources

EEA DataHub and WISE EU portal were the foundational data sources for chapters 1,2 and 4.

To develop chapter 5 and 6, these sources needed to be complemented with web and literature research. The main platforms used for literature research were:

- Google scholar
- Science Direct
- Academia.edu
- Taylor & Francis Online
- MDPI

The main types of websites accessed were:

- Water and wastewater private and public managing authorities
- Municipalities official websites
- Engineering and Construction companies
- Geodata collectors
- Local newspapers

Typical key words used during the searches for the development of chapter 5 and 6 were:

“WWTP”, “scheme of treatment”, “process diagram”, “water line”, “treatment steps”, “process scheme”, “performances”, “resource consumption”, “LCA, chemicals usage”, “electricity demand”, “footprint”, “land demand”, “sludge production”

Chapter 7 relied both on literature review and web research. Frequently consulted websites slightly differed from the case of chapter 5 and 6 with as typical sources theoretical websites.

Typical key words used during the searches for the development of chapter 7 were:

“BNR”, “biological nutrients removal”, “A2/O”, “A/O”, “key factors”, “principles”, “SRT”, “MLSS”, “HRT”, “anoxic”, “aerobic”, “anaerobic”, “influent”, “retrofit”, “investments”, “costs”, “CAS”

Sources for chapter 8 building were searched similarly to the case of chapter 5 and 6 but with, as typical key words:

“WWTP”, “retrofitting”, “upgrading”, “nutrients removal”, “CAS”, “investments”, “costs”, “AGS”, “MABR”, “MBR”, “IFAS”, “MBBR”

3.3 Data Processing and Classification

During the web research for water line treatment schemes, operative performances and case studies all information found was somehow used. Due to the lack of sources an effort to extract valuable information from each source was accomplished. No screening or prioritization of the sources was done.

3.4 Methodology for Portuguese WWTP Analysis

All the 529 Portuguese WWTPs initially present in the dataset were considered.

The determination of the 108 WWTPs requiring upgrade for what concerns nutrients removal was based on the available values of design size capacity (pe) and discharge zone eutrophication risk level.

WWTPs with a design capacity above 150 000 pe were included in the group requiring retrofit irrespective of the type of discharge area they were connected to, while WWTPs between 10 000 and 150 000 pe were added to the group only if discharging in eutrophication sensitive areas.

Discharge areas labelled as Normal Areas (NA) were the only ones excluded from the eutrophication sensitive group. All the other areas, including Less Sensitive Areas (LSA) were considered equally sensitive using a conservative approach.

3.5 Methodology for Process Characterisation

98 of the 108 Portuguese WWTPs to retrofit were grouped according to the following factors:

- Level of treatment achieved (primary, secondary, tertiary due to a disinfection or filtration step, tertiary due to nutrients removal)
- Design size capacity (low, medium, high)
- Type of primary treatment step (complete vs incomplete)
- Type of bioreactor used in secondary treatment step (continuous vs batch; suspended biomass vs fixed biomass; aerobic only vs aerobic/anoxic and aerobic/anoxic/anaerobic)
- Presence of secondary sedimentation step (complete vs incomplete)

10 WWTPs to retrofit were excluded from the analysis possessing a quite high starting level of treatment (tertiary due to the presence of 1 nutrient removal unit over the 2 required) and a very little design capacity.

A group of interest composed of 68 WWTPs either lacking a secondary treatment step, or possessing a continuous suspended biomass bioreactor, resulted from the process characterization.

The derivation of average performances for these 68 WWTPs was based on the analysis of the data retrieved during the web research complemented by the few originally available data in the dataset in terms of pollutants incoming and outcoming loads and volume treated.

Sourcing uniquely from the web research, information on energy consumption, sludge production and land demand was at times added.

3.6 Methodology for Danish Benchmark Analysis

Danish WWTPs above 10 000 pe design capacity were selected.

Through available data on incoming and outcoming pollutant loads and volumes treated, effluent composition and nutrients removal percentages were computed.

127 WWTPs possessing the following requirements were selected:

- N content in treated effluent below 8 mg/L
- P content in treated effluent below 0,7 mg/L
- N % removal above 85%
- P % removal above 90%

118 of these 127 WWTPs possess a design capacity below 150 000 pe. Which means that for them these requirements exceed those that the new directive expects from them.

8 out of the remaining 9 WWTPs above 150 000 pe design capacity fulfilling all these requirements have also a P effluent concentration below 0,5 mg/L, which means that they too exceed the new directive requirements. Only one WWTP has a P content around 0,6 mg/L in its effluent.

Overall, the 127 WWTPs identified can be considered a representative sample for reference WWTPs in terms of nutrients removal.

Similarly to the procedure followed for the Portuguese group of interest, a web and literature research was performed to derive the water line most common configurations for these reference WWTPs.

Danish WWTPs were clustered based on the similarity of the found water line treatment schemes, both in terms of infrastructure and strategies adopted. Relevant infrastructure elements considered during the clustering process for Danish WWTPs were the following:

- Preliminary screening and sieving
- Sand grit and grease tanks
- Primary coagulation-flocculation separate tanks
- Storm water storage tanks
- Sedipac primary tanks/Multiflow/actiflow-Compact primary treatment steps
- equalization tanks
- Salsnes filter for C harvest
- Primary sedimentation tanks
- Continuous suspended biomass-A/O + BAF
- Continuous suspended biomass-A/O
- Continuous suspended biomass-A2/O
- Continuous suspended biomass-A2/O + BAF
- secondary sedimentation tanks
- online sensors connected to a SCADA for extensive automation and online control

- Digital twin model of the WWTP

Relevant operative strategies considered during the clustering process for Danish WWTPs were the following:

- Granular sludge Recycle technology to improve settleability
- Activated return sludge (to improve sludge settleability and reduce excess sludge production)
- raw influent fermentation to prepare it for EBPR
- Recycled sludges fermentation to prepare EBPR
- recycled reject water from sludge line fermentation to prepare influent for EBPR
- Extra C source dosing for denitriphication step
- Intermittent aeration in aerobic tanks (no need of specific anoxic tanks)
- Chemicals dosing for P precipitation
- side stream NH4 removal step on liquors recycled from sludge line back to water line
- Polyelectrolyte dosing for coagulation/flocculation
- Final reaeration

3.7 Limitations of the Methodology

Apart from the analysis based on the EU dataset, which is quite consistent, the heavily web research oriented approach followed to determine the water lines and the performances of Portuguese and Danish WWTPs of interest has severe limitations here recapped:

For most of the WWTPs the treatment scheme found was not detailed leaving large doubts on the specific configurations adopted in the bioreactors and on the side strategies implemented to improve the overall performances. The level of information publicly achievable usually limited to black box diagrams with information retrievable similar to that already found in the EU dataset.

Several times incongruencies between the information reported on the EU dataset and those found on the web were highlighted.

Most of the treatment schemes found date back to more than 15 years ago, leaving open the possibility that major modifications to the process scheme have been performed in the meanwhile leading to not up to date configurations, which may also be an explanation for some of the incongruencies with the EU dataset.

Data on WWTPs performances were derived from the web research in a highly scattered way, with the usage of different sources combined to derive values for single WWTPs.

Averages over multiple WWTPs performances were based on values derived for single WWTPs sourcing from different years.

The number of WWTPs for which data were actually derived, especially in terms of performances, was very low, leading to poorly trustable averages due to the limited size of the sample at their basis.

Lastly, the economic evaluation of possible retrofits or greenfield works to adapt WWTPs to the new standards also sourced from a very limited web research, with few and not detailed data publicly available.

4 Characterisation of Portuguese WWTPs Based on EU Data

4.1 Overview of Portuguese WWTP System

In the following part of the work, the focus will be on the Portuguese situation, trying to characterize the wastewater treatment plants distribution in terms of size, level of treatment, nutrients removal units and discharge points. The analysis goal is identifying the number of plants that will need to be updated according to the new directive. For the sake of this work a conservative approach will be taken and it will be considered that, the plants that already implement specific N and P removal units, reach at maximum the limits reported in Table 2-1: EU Council Directive of May 1991, UWWTD, Nutrients removal expected performances (Council Directive of May 1991, urban wastewater treatment directive,1991) and so need however to be adapted if their size and discharge points require it. Obviously, a different kind of retrofit will be required to plants that already have nutrients removal units compared to those that don't present it.

The total design load of the nation is 17 364 518 pe according to EU datasets (Datahub (EEA), 2025). The big plants can treat a load of 8 780 197 pe, Figure 4.1, which represents 50,6% of the national load capacity. All these 29 big plants will need to be retrofitted by law.

To identify the remaining WWTPs that by law will need retrofits to adapt their standards it is essential to characterize now the discharge points of the medium sized plants. From Figure 4.2. what emerges is that, of the 189 medium sized plants in Portugal, 79 are discharging into sensitive areas (being conservative also less sensitive areas are considered sensitive) representing with 3 191 041 pe (Datahub (EEA) , 2025), 44,7% of the load capacity of medium sized plants and 18,37% of the national one.

So, according to EU datasets we have 29 big plants and 79 medium sized plants that need retrofit, with a treating capacity equal to 11 971 238 pe, that is 68,9% of the national one.

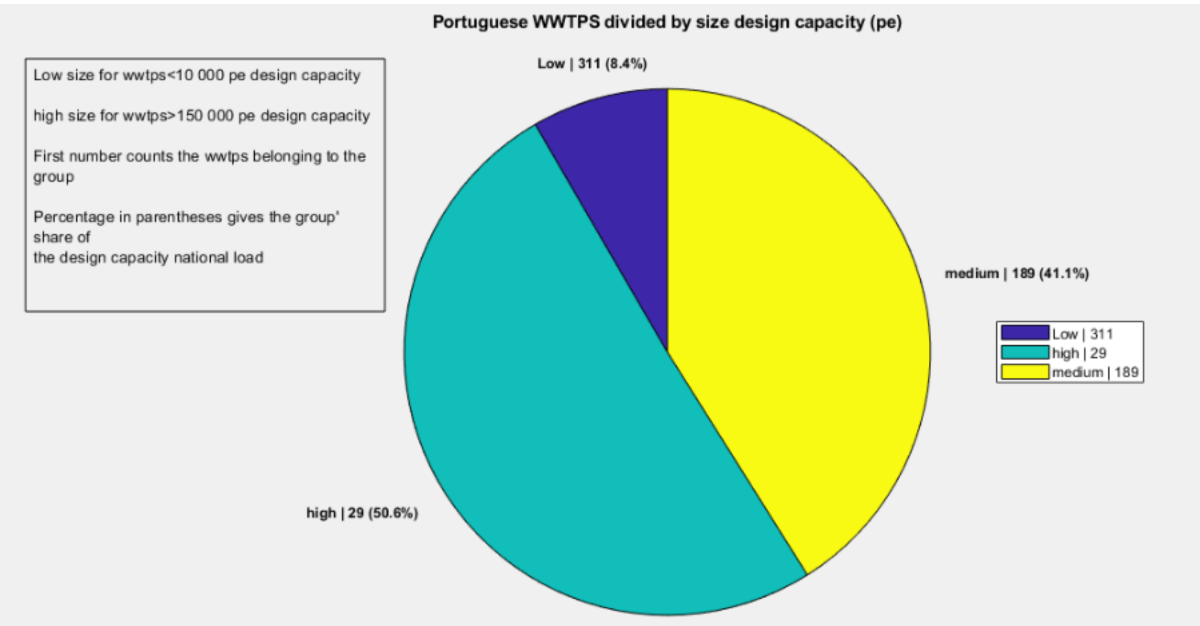


Figure 4.1: Portuguese WWTPs divided by size (DataHub, EEA, 2025)

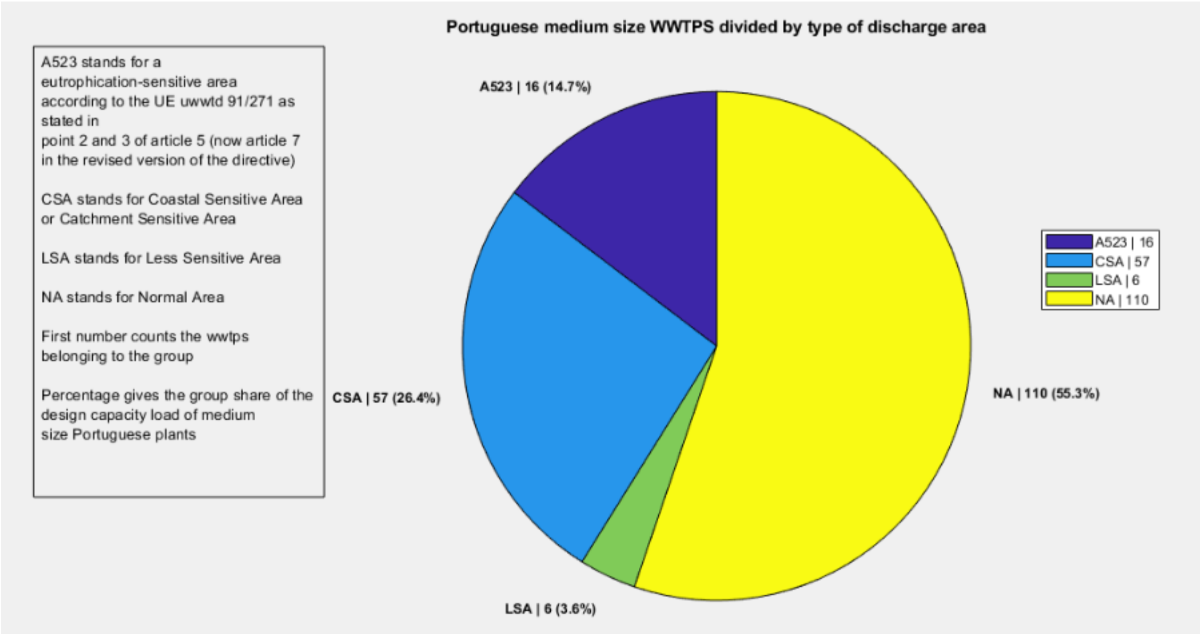


Figure 4.2: Medium size Portuguese WWTPs divided by type of discharge area (DataHub, EEA, 2025)

To deepen the characterization, the rest of the chapter's goal will be to classify these plants to be retrofitted based on the level of treatment achieved, starting with medium sized plants discharging into sensitive areas, to then move on to the high size ones.

4.2 Analysis of Medium-Sized WWTPs discharging in sensitive areas

Of the 79 medium size plants discharging in sensitive areas, 6 achieve only primary level, with a capacity load of 259 615 pe (1,49% of national load), and 17 are secondary level plants, (Figure 4.3), with a capacity load of 577 796 pe (3,32% of national load). All these WWTPs will need a complete upgrade having no specific nutrients removal unit.

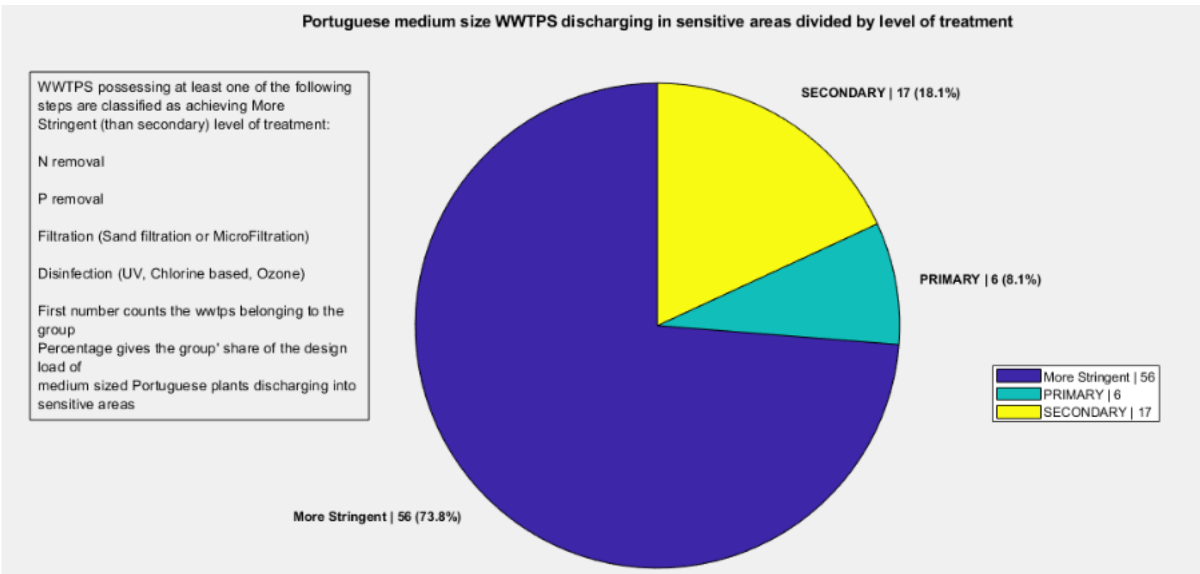


Figure 4.3: Medium size Portuguese WWTPs discharging into sensitive areas divided by level of treatment achieved (DataHub, EEA, 2025)

For the primary level ones the introduction of an organic matter removal step able to target also nutrients could allow them to do simultaneously the two steps improvement required.

Even among the 56 WWTPs reaching more stringent level of treatment there might be some that completely lack nutrients removal units. Next step will be to analyze them in terms of N&P removal units.

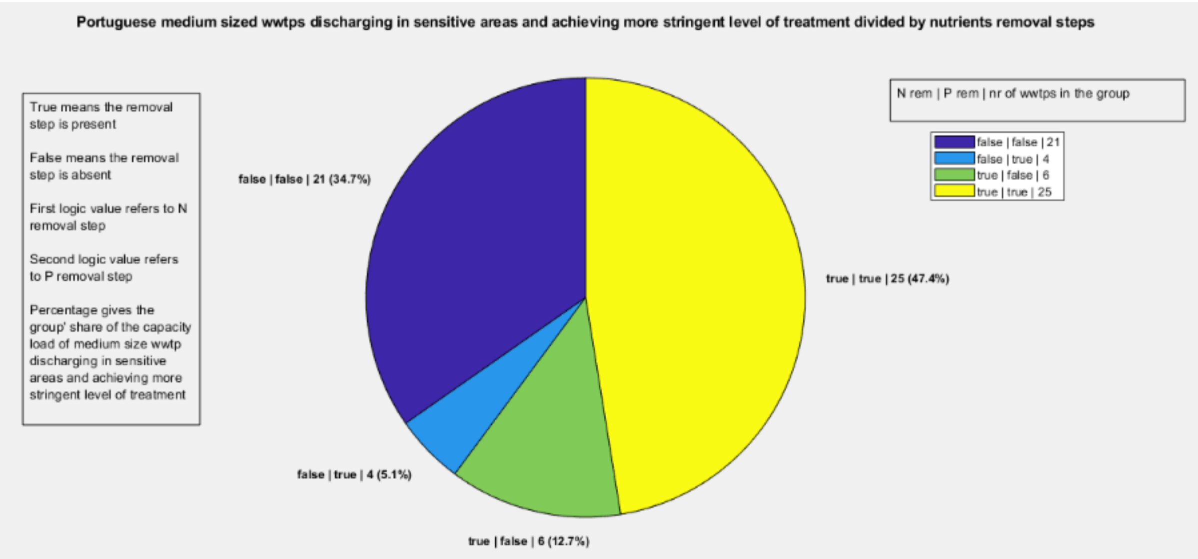


Figure 4.4: Portuguese medium sized WWTPs discharging in sensitive areas and achieving more stringent level of treatment divided by nutrients removal steps (DataHub, EEA, 2025)

Of the 56 medium sized plants discharging into sensitive areas and achieving more stringent level of treatment, 21, with a design load of 816 782 pe (4,7% of national load), must be included in the group requiring complete retrofit. (Figure 4.4) These WWTPs probably achieve more stringent level of treatment status thanks to the presence of disinfection or filtration steps.

Treatment plants won't be classified also in terms of filtration or disinfection units since these are not relevant for nutrients removal unless aiming at removing very fine particles of precipitated P, or considering biofiltration units.

It is possible to identify four main categories for the medium sized plants requiring upgrading:

- Nutrients removal units to be installed (no nutrients removal units present)
- N removal units to be installed (no N removal unit present)
- P removal units to be installed (no P removal unit present)
- Nutrients removal units to be upgraded (nutrients removal units present)

Table 4-1: medium size plants discharging into sensitive areas retrofitting classification

medium size plants discharging in sensitive areas				
treatment level	load (pe)	number of plants	retrofit required	% of national load
primary	259 615	6	S+N+P installation	1,50
secondary	577 796	17	N+P installation	3,33
more stringent without nutrients removal	816 782	21	N+P installation	4,70
more stringent with P removal	120 959	4	N installation	0,70
more stringent with N removal	299 292	6	P installation	1,72
more stringent with nutrients removal	1 116 597	25	N+P update	6,43

Legend: S stands for secondary treatment; N stands for N removal; P stands for P removal

Considering that disinfection and filtration units do not significantly influence nutrients removal performances, it might be reasonable to merge into one group secondary level WWTPs and more stringent level-without nutrients removal WWTPs, since, in the perspective of nutrients removal, they behave the same way.

Table 4-2: medium size plants discharging into sensitive areas merged retrofitting classification

medium size plants discharging in sensitive areas			
retrofit required	load (pe)	number of plants	% of national load
S+N+P installation	259 615	6	1,50
N+P installation	1 394 578	38	8,03
N installation	120 959	4	0,70
P installation	299 292	6	1,72
N+P update	1 116 597	25	6,43

In the following section large, big size and High size are used interchangeably.

4.3 Analysis of Large WWTPs

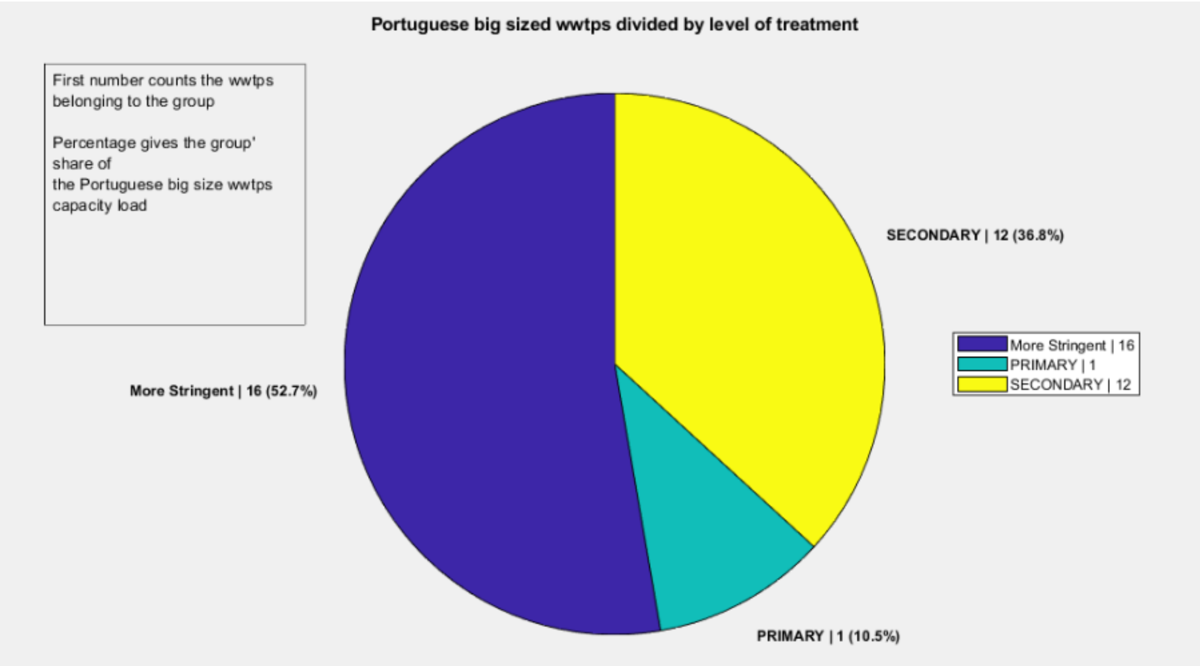


Figure 4.5: Portuguese WWTPs of high size divided by the level of treatment achieved (DataHub, EEA, 2025)

Of the 29 high size WWTPs, 1 achieves only primary level, with a capacity load of 920 000 pe (5,3% of national load), and 12 are secondary level plants, with a capacity load of 3 231 440 pe (18,6% of national load. These 13 WWTPs will need a complete upgrade having no specific nutrients removal unit. The analysis continues with the 16 plants reaching more stringent level studying them in terms of N&P removal units.

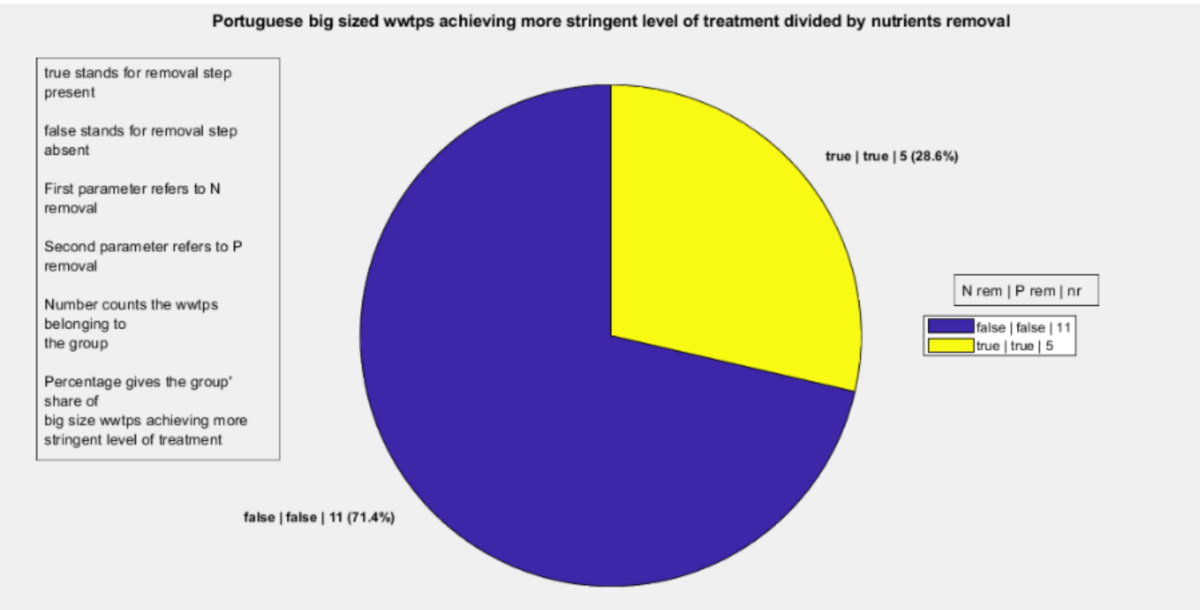


Figure 4.6: Big size WWTPs with more stringent level of treatment divided by nutrients removal units (DataHub, EEA, 2025)

Out of the 16 big size WWTPs achieving more stringent level of treatment 11 completely lack nutrients removal but must have at least one amid disinfection or filtration step. Repeating the same reasoning done with medium size WWTPs, a first upgrading classification is created in Table 4-3, to then merge secondary level and more stringent level with no nutrients removal into one single group with Table 4-4 .

Table 4-3: High size WWTPs retrofitting classification

high size plants				
treatment level	load (pe)	number of plants	retrofit required	% of national load
primary	920000	1	S+N+P installation	5,30
secondary	3231440	12	N+P installation	18,61
more stringent without nutrients removal	3305741	11	N+P installation	19,04
more stringent with P removal	0	0		0,00
more stringent with N removal	0	0		0,00
more stringent with nutrients removal	1323016	5	N+P update	7,62

Table 4-4: High size WWTPs merged retrofitting classification

high size plants			
retrofit required	load (pe)	number of plants	% of national load
S+N+P installation	920000	1	5,30
N+P installation	6537181	23	37,65
N installation	0	0	0,00
P installation	0	0	0,00
N+P update	1323016	5	7,62

To end this preliminary clustering analysis, results from medium and big size WWTPs will be combined to get an overall view of the most common macro-families of starting Portuguese situations to be retrofitted. (

Table 4-5)

When considering a retrofit strategy, the kind of starting situation of the WWTP to retrofit is of capital relevance. These macro-families should be look at as common starting situations for the Portuguese WWTPs to retrofit.

However, to be able to suggest retrofitting strategies, more than a characterization of the possible starting situations in terms of level of treatment achieved (which is the result of this chapter), what's needed is a characterization of the possible starting process configurations relevant for nutrients removal. This will be the objective of the following chapter.

Table 4-5: Portuguese WWTPs merged retrofitting classification

	Portuguese WWTPs to retrofit family's subdivision				
	Family	retrofit required	load (pe)	number of plants	% of national load
1	big size-primary	S+N+P installation	920 000	1	5,3
2	big size-secondary or more stringent without nutrients removal	N+P installation	6 537 181	23	37,6
3	big size-nutrients removal	N+P update	1 323 016	5	7,6
4	mid size-primary	S+N+P installation	259 615	6	1,5
5	mid size-secondary or more stringent without nutrients removal	N+P installation	1 394 578	38	8,0
6	mid size-P rem	N installation	120 959	4	0,7
7	mid size-N rem	P installation	299 292	6	1,7
8	mid size-nutrients removal	N+P update	1 116 597	25	6,4

4.4 Chapter Summary and Key Findings

- Portugal possesses 529 WWTPs above 2000 pe design capacity
- 29 of these 529 WWTPs are above 150 000 pe and can deal with more than 50% of national design treatment capacity
- All the 311 WWTPs below 10 000 pe design size, combined have less than 10% of the national design treatment capacity
- 79 out of the 189 medium sized WWTPs (10 000-150 000 pe), discharge their effluents in eutrophication sensitive areas, representing more than 18% of national design treatment capacity.
- Overall 108 WWTPs representing more than 68% of national design treatment capacity require nutrients removal upgrade.
- Only 30 out of these 108 WWTPs (25 medium size and 5 large), having 14 % of the national design treatment capacity, already implement some sort of nutrients removal. These will probably require just an update of their existing infrastructure.
- All the other 78 instead, will require the introduction of at least one brand new nutrient removal step, with 7 WWTPs (6 medium, 1 large) still lacking a complete secondary treatment step (7% of national capacity)

5 Identification and Process Characterisation of Priority Portuguese WWTPs

Objective of the chapter will be identifying common starting configurations of the Portuguese WWTPs to retrofit. To do so there's the need to refine and deepen the analysis getting more detailed information on the water line nutrients removal steps that Portuguese WWTPs to retrofit adopt. This kind of information is not retrievable from the EU dataset and will be looked for on the web.

5.1 Identification of priority WWTPs

Before diving into the clustering of Portuguese WWTPs according to the water line nutrients removal sequences they adopt, a hierarchy between the macro-families of treatment plants requiring upgrading will be created to understand which to prioritize for the retrofit assessment.

The logic behind the hierarchy creation relies on two family factors: level of treatment achieved and share of the national load.

Treatment plants macrofamilies with higher share of the national capacity load or with primary level of treatment will be considered more urgent to retrofit than those achieving more stringent level of treatment or having the capacity to treat a lower load.

Based on this logic, the initial 8 macro-families of WWTPs to retrofit resulting from the preliminary analysis, (

Table 4-5), will be divided into two groups: priority and non-priority group (

Table 5-1).

Only the WWTPs belonging to macro-families considered priority will be the object of the analysis conducted in this chapter.

Table 5-1: Priority vs non-Priority group

		Portuguese WWTPs to retrofit priority subdivision				
Previous number	updated number	Family	retrofit required	load (pe)	number of plants	% of national load
1	1	big size-primary	S+N+P installation	920000	1	5,3
2	2	big size-secondary (with Dis/Filt)	N+P installation	6537181	23	37,6
3	3	big size-nutrients removal	N+P update	1323016	5	7,6
4	4	mid size-primary	S+N+P installation	259615	6	1,5
5	5	mid size-secondary (with Dis/Filt)	N+P installation	1394578	38	8,0
8	6	mid size-nutrients removal	N+P update	1116597	25	6,4

6	7	mid size-P rem	N installation	120959	4	0,7
7	8	mid size-N rem	P installation	299292	6	1,7

Highlighted in yellow are the macro-families of WWTPs belonging to the priority group. Treatment plants belonging to macro-family 6 and 7 in the original numeration were excluded from the priority group having a low capacity and starting from a quite high level of treatment (more stringent, lacking just one of the two nutrients removal units). From now on the macrofamilies numeration will reflect the updated one.

5.2 Clustering of priority WWTPs in subgroups according to water line structure

Having identified which are the specific macro-families of treatment plants to focus on, the analysis will aim at clustering the WWTPs of each priority macro-family in subgroups based on shared water line sequences of nutrients removal step.

Sludge line treatment steps won't be considered relevant for the scope of this clustering since nutrients removal highest contribution comes from water line. Whereas, if aiming at nutrients recovery retrofits, sludge line could not be disregarded during the clustering process.

To retrieve the water line description of the WWTPs belonging to the macro-families involved (reported in annex 2) web research is conducted. Thesis works and reports from official wastewater managing companies are privileged as relevant sources to fill the voids of the EU dataset. The external sources used to derive the water line sequences are reported in the excel table included in annex 2.

Sometimes the web sources show some incongruencies with what was reported in the EU dataset. Not being able to say with absolute confidence which source is more trustworthy, annex 2 and the following subgrouping figures just highlight in yellow the names of the WWTPs with profile mismatches.

Examples of mismatches considered relevant are:

- EU primary level treatment WWTP possessing a secondary treatment step or lacking primary sedimentation
- EU secondary level treatment WWTP possessing either an anaerobic reactor in addition to the aeration one, A2/O bioreactor, A/O bioreactor or adopting chemical P removal
- EU nutrients removal WWTP not showing either an A2/O bioreactor or a A/O bioreactor coupled with chemical P removal

Mismatches regarding disinfection and filtration units were not highlighted since these units are not considered actively involved in nutrients removal. It is important to notice that most of the treatment schemes found on the web date back to more than 10 years ago. This means that it's possible that Portuguese plants upgraded their schemes in the meanwhile and this could also be the reason behind some mismatches with what's reported in EU dataset that was compiled in 2022. The clustering resulting from the above-mentioned research will be presented through figures, summarizing, for each sub-group identified, the main water line nutrients removal steps present. Possible water line steps typically present but missing in specific cases will also be reported. In the figures the reader will see subgroups of WWTPs sharing the same sequence of presence/absence of treatment steps in their water lines.

A legend is now given to help the reader understand the figures.

Screening and sieving will be labelled as preliminary step.

Sand-grit-grease removal and primary sedimentation will be labelled as primary step.

Treatment plants possessing at least one among the following configurations will be classified as having a full primary treatment step:

- Primary sedimentation tank
- Sand-grit-grease removal tank + primary sedimentation tank
- Compact primary treatment tank (such as Sedipac® from Suez or Multiflo™ from Veolia)
- Primary coagulation-flocculation-sedimentation tank

Then the kind of bioreactor used and the secondary sedimentation step will be pointed out.

For what concerns the bioreactor it will be studied according to three factors:

- Continuous vs batch system
- Suspended vs fixed biomass system
- Aerobic only vs A/O or A2/O systems

Even if never explicitly considered water line nutrients removal steps, the following units are essential for the success of the nutrients removal performance:

- preliminary screening and sieving
- sand-grit-grease removal tanks
- primary sedimentation tanks

These steps in fact influence the organic and TSS load on the bioreactor, known to be important factors in the nutrients removal process (Mishra et al., 2022), (Son et al., 2020). For this reason, their presence or absence is considered a relevant parameter in the clustering process. Secondary sedimentation too is included among the relevant steps for nutrients removal, allowing the separation of the treated effluent from the sludges and solids resulting from the organic and nutrients removal steps, hindering biomass carryover with the effluent.

Treatment plants for which the water line scheme was not found were excluded from the clustering process and mentioned in Table 5-2,

Table 5-3, and Table 5-4.

Table 5-2: Macrofamily 4-WWTPs with unavailable water line schemes

FAMILY 4	Mid size-primary level-unavailable schemes	Design load (pe)	% of national design load
1 WWTP	Canico	27000	0,2

Table 5-3: Macrofamily 5-WWTPs with unavailable water line schemes

FAMILY 5	Mid size-secondary level /no nutrients removal-unavailable schemes	Design load (pe)	% of national design load
12 WWTPs	Rio Ferreira	35000	0,20
	Vilar Formoso	10500	0,06
	Vila Nova da Barquinha	10793	0,06
	Marinhais	10884	0,06
	S. Pedro	25000	0,14
	Almeirim/Alpiarca	29342	0,17
	Ponte de Lima	20457	0,12
	Fiaes /S. Jorge	46000	0,26
	Ponte de Sor	16081	0,09
	Lapas	10300	0,06
	Campo (Valongo, Campo e Sobrado)	98278	0,57
	Silves	15500	0,09
	TOTAL	328135	1,9

Table 5-4: Macrofamily 6-WWTPs with unavailable water line schemes

FAMILY 6 (Previous 8)	Mid size-nutrients removal-unavailable schemes	Design load (pe)	% of national design load
10 WWTPs	Lamego	19300	0,11
	Peso da Regua	25000	0,14
	Vila Real	84321	0,49
	Vila Mea	12771	0,07
	S. Miguel	40000	0,23
	Reguengos de Monsaraz	11050	0,06
	Chaves	57748	0,33
	Nelas III	14633	0,08
	Poente de Mangualde	12200	0,07
	Afonsoeiro	47940	0,28
	TOTAL	324963	1,87

From now on secondary level refers to both, secondary level WWTPs, and tertiary level ones because of disinfection and/or filtration units. Big size and High size are again used interchangeably.

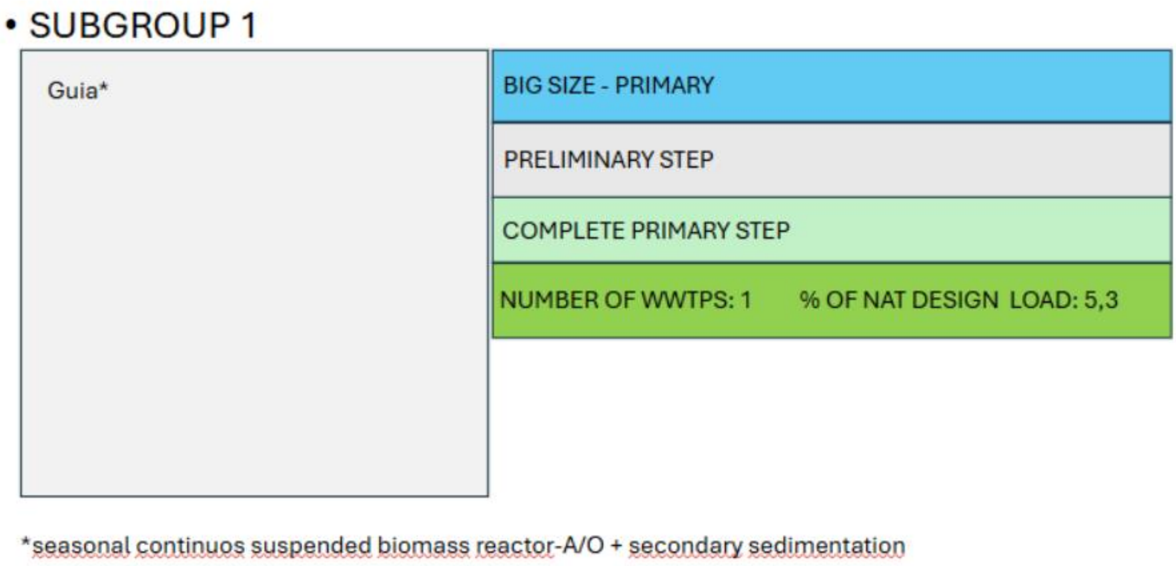


Figure 5.1: Subgroup 1-Big size-primary level-complete primary step

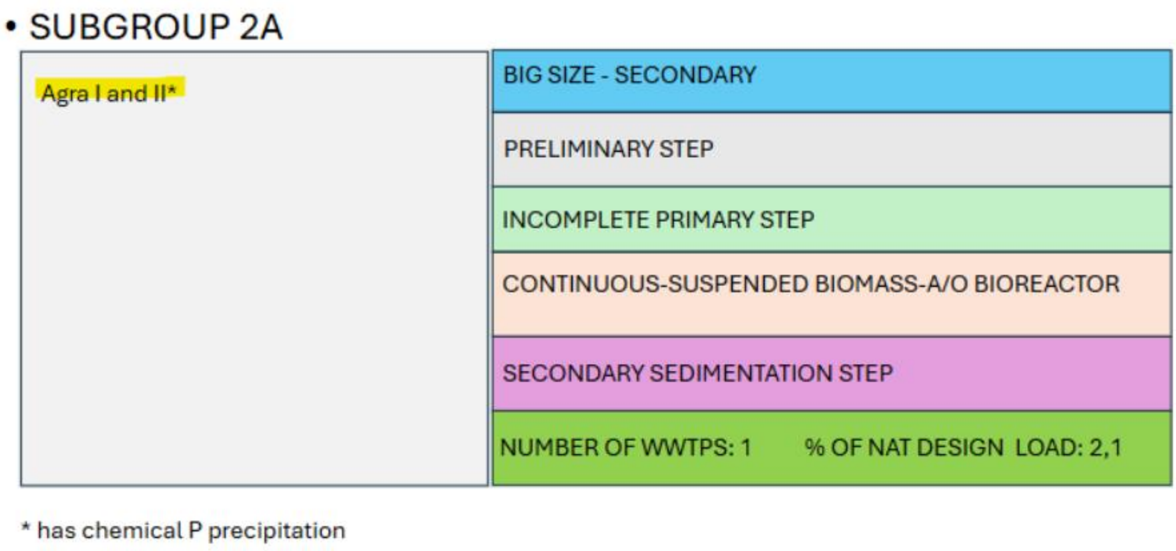


Figure 5.2: Subgroup 2A-Big size-secondary level-incomplete primary step-continuous suspended biomass-A/O bioreactor

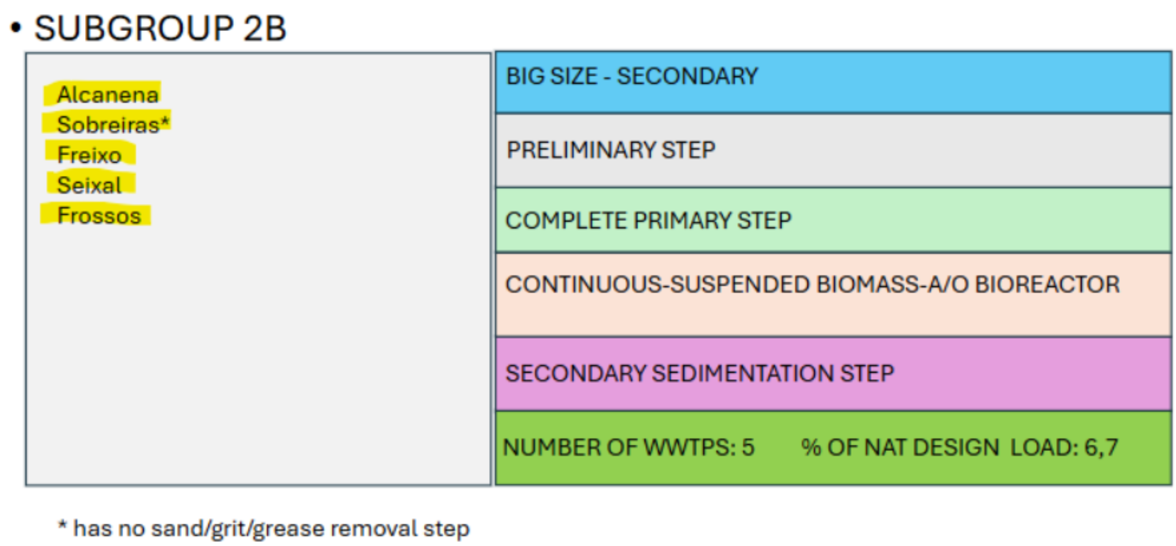


Figure 5.3: Subgroup 2B-Big size-secondary level-complete primary step- continuous suspended biomass-A/O bioreactor

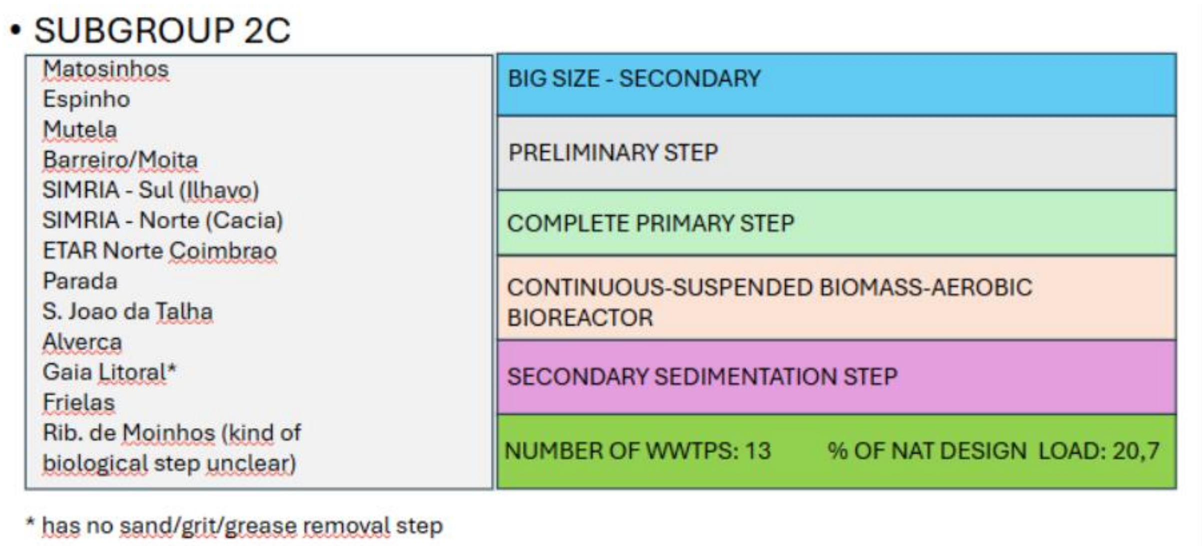


Figure 5.4: Subgroup 2C-Big size-secondary level-complete primary step-continuous suspended biomass aerobic bioreactor

- SUBGROUP 2D

Choupal Quinta da Bomba Alcantara*	BIG SIZE - SECONDARY
	PRELIMINARY STEP
	COMPLETE PRIMARY STEP
	FIXED BIOMASS-BIOREACTOR
	SECONDARY SEDIMENTATION STEP
	NUMBER OF WWTPS: 3 % OF NAT DESIGN LOAD: 6,7

*It has no secondary sedimentation step

Figure 5.5: Subgroup 2D-Big size-secondary level-complete primary step-continuous fixed biomass bioreactor

- SUBGROUP 2E

Ave	BIG SIZE - SECONDARY
	PRELIMINARY STEP
	COMPLETE PRIMARY STEP
	CONTINUOUS SUSPENDED BIOMASS-A2/O-BIOREACTOR
	SECONDARY SEDIMENTATION STEP
	NUMBER OF WWTPS: 1 % OF NAT DESIGN LOAD: 1,5

Figure 5.6: Subgroup 2E-Big size-secondary level-complete primary step-continuous suspended biomass-A2/O bioreactor

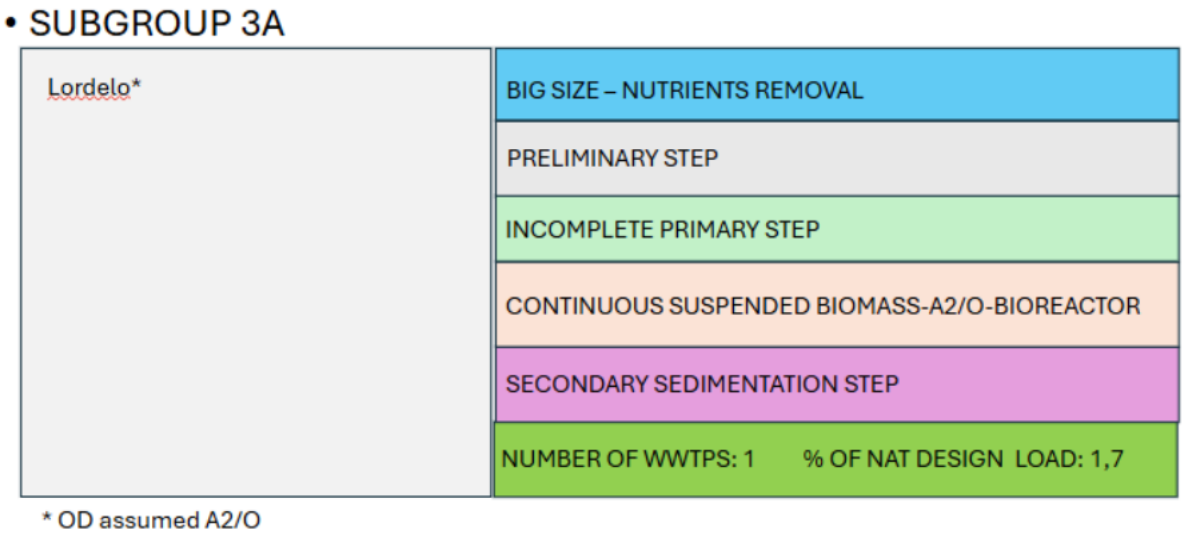


Figure 5.7: Subgroup 3°-Big size-nutrients removal-incomplete primary step-continuous suspended biomass-A2/O bioreactor

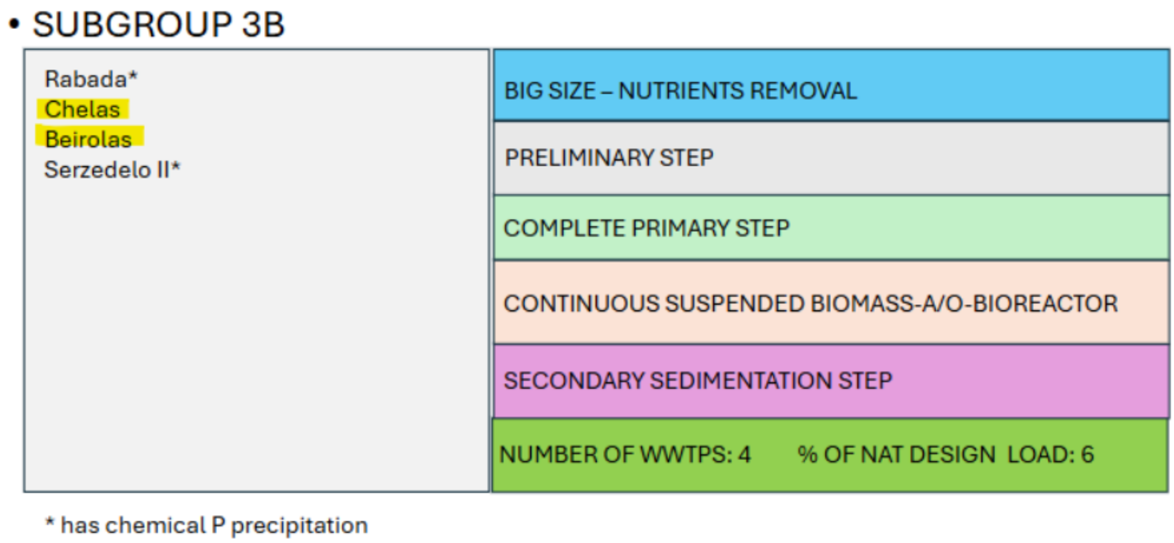


Figure 5.8: Subgroup 3B-Big size-nutrients removal-complete primary step-continuous suspended biomass-A/O bioreactor

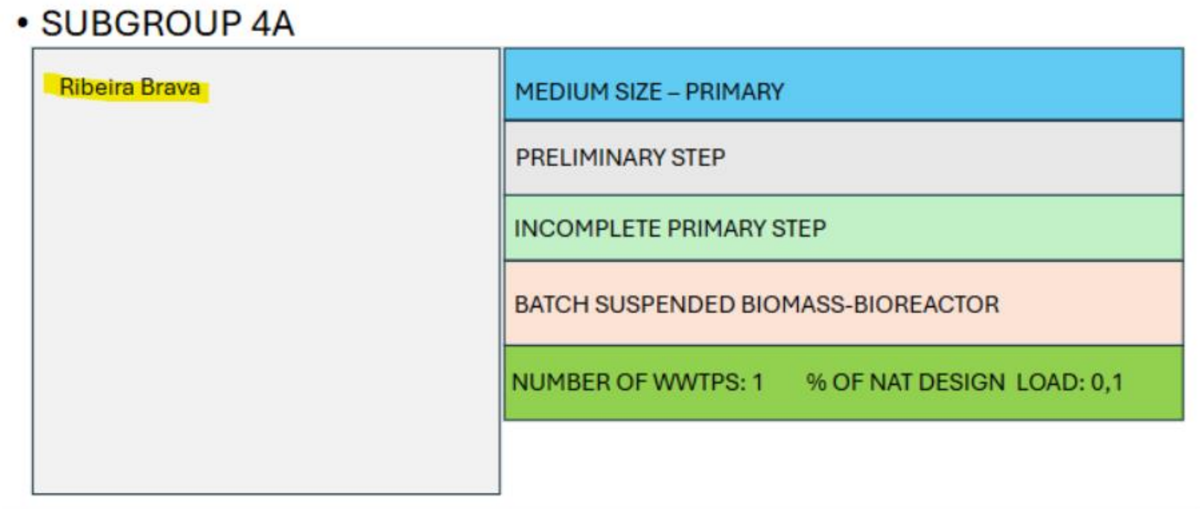


Figure 5.9: Subgroup 4°- medium size-primary level-incomplete primary step-batch suspended biomass bioreactor

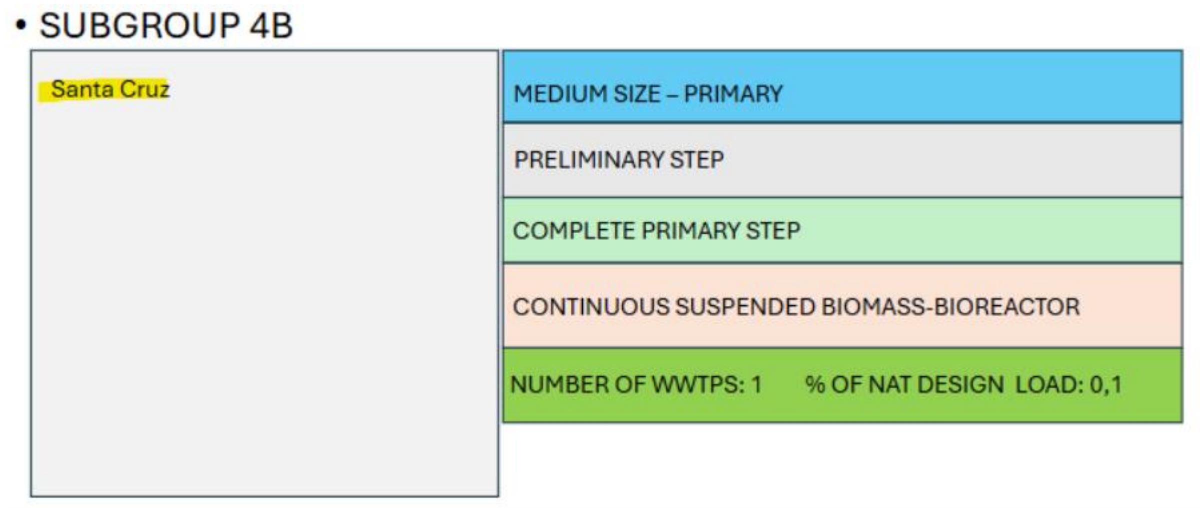


Figure 5.10: Subgroup 4B- medium size-primary level-complete primary step-continuous suspended biomass bioreactor

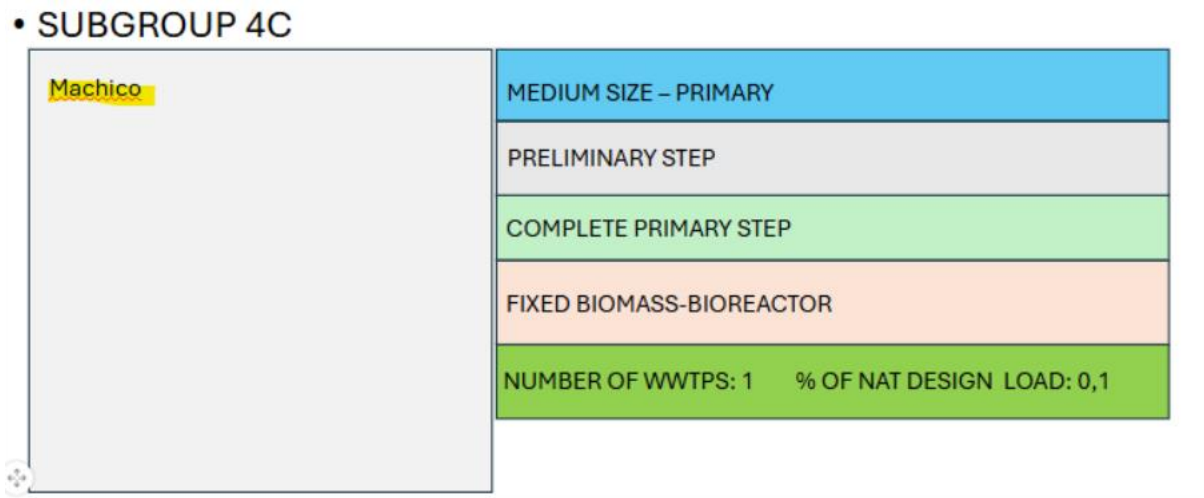


Figure 5.11: Subgroup 4C-medium size-primary level-complete primary step-fixed biomass bioreactor

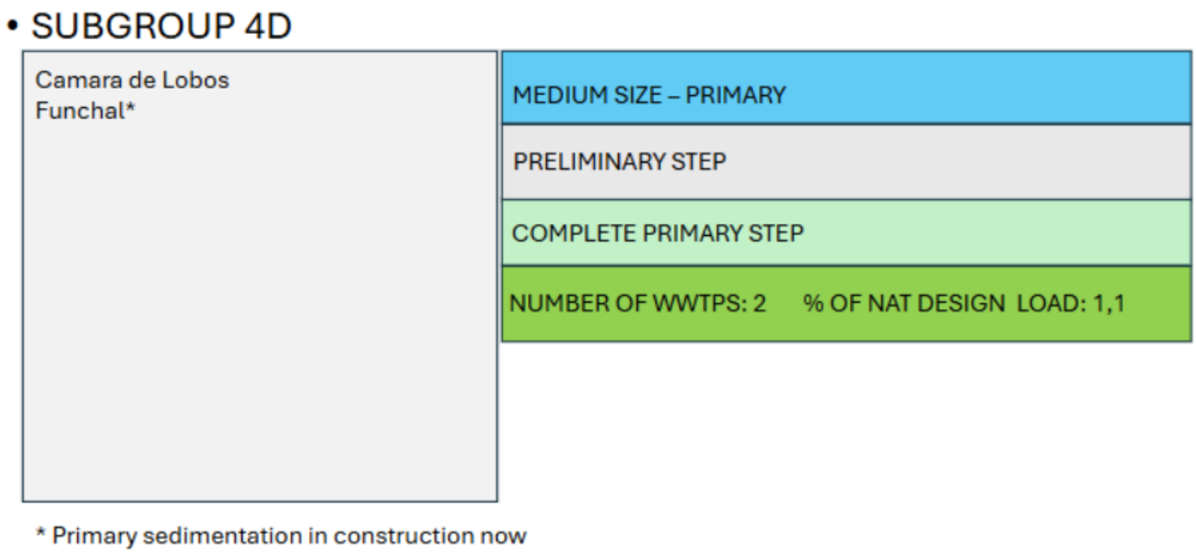


Figure 5.12: Subgroup 4D-medium size-primary level-complete primary step

- SUBGROUP 5A

Santa Cita Almargem Faro-Noroeste Alto Nabao*	MEDIUM SIZE – SECONDARY
	PRELIMINARY STEP
	INCOMPLETE PRIMARY STEP
	CONTINUOUS-SUSPENDED BIOMASS-A/O BIOREACTOR
	SECONDARY SEDIMENTATION STEP
	NUMBER OF WWTPS: 4 % OF NAT DESIGN LOAD: 1,1

*has chemical P precipitation

Figure 5.13: Subgroup 5°-medium size-secondary level-incomplete primary step-continuous-suspended biomass-A/O bioreactor

- SUBGROUP 5B

Entroncamento	MEDIUM SIZE – SECONDARY
	PRELIMINARY STEP
	INCOMPLETE PRIMARY STEP
	CONTINUOUS-SUSPENDED BIOMASS-A2/O BIOREACTOR
	SECONDARY SEDIMENTATION STEP
	NUMBER OF WWTPS: 1 % OF NAT DESIGN LOAD: 0,1

Figure 5.14: Subgroup 5B-medium size-secondary level-incomplete primary step-continuous-suspended biomass-A2/O bioreactor

- SUBGROUP 5C

Seixalinho*

MEDIUM SIZE – SECONDARY

PRELIMINARY STEP

INCOMPLETE PRIMARY STEP

BATCH SUSPENDED BIOMASS BIOREACTOR

NUMBER OF WWTPS: 1 % OF NAT DESIGN LOAD: 0,3

*has an anoxic selector before the SBR and a lagoon after instead of the secondary sedimentation

Figure 5.15: Subgroup 5C-medium size-secondary level-incomplete primary step-batch-suspended biomass- bioreactor

- SUBGROUP 5D

Alcacer do Sal Norte (Nova ETAR)
Lever
Fatima
Seica*
Argoncilhe*
Lagoinha*
Zona Urbana (Vila Verde)
Olhao Nascente

MEDIUM SIZE – SECONDARY

PRELIMINARY STEP

INCOMPLETE PRIMARY STEP

CONTINUOUS-SUSPENDED BIOMASS-AEROBIC BIOREACTOR

SECONDARY SEDIMENTATION STEP

NUMBER OF WWTPS: 8 % OF NAT DESIGN LOAD: 1,3

*primary sedimentation assumed absent since not visible

Figure 5.16: Subgroup 5D- medium size-secondary level-incomplete primary step-continuous suspended biomass-aerobic bioreactor

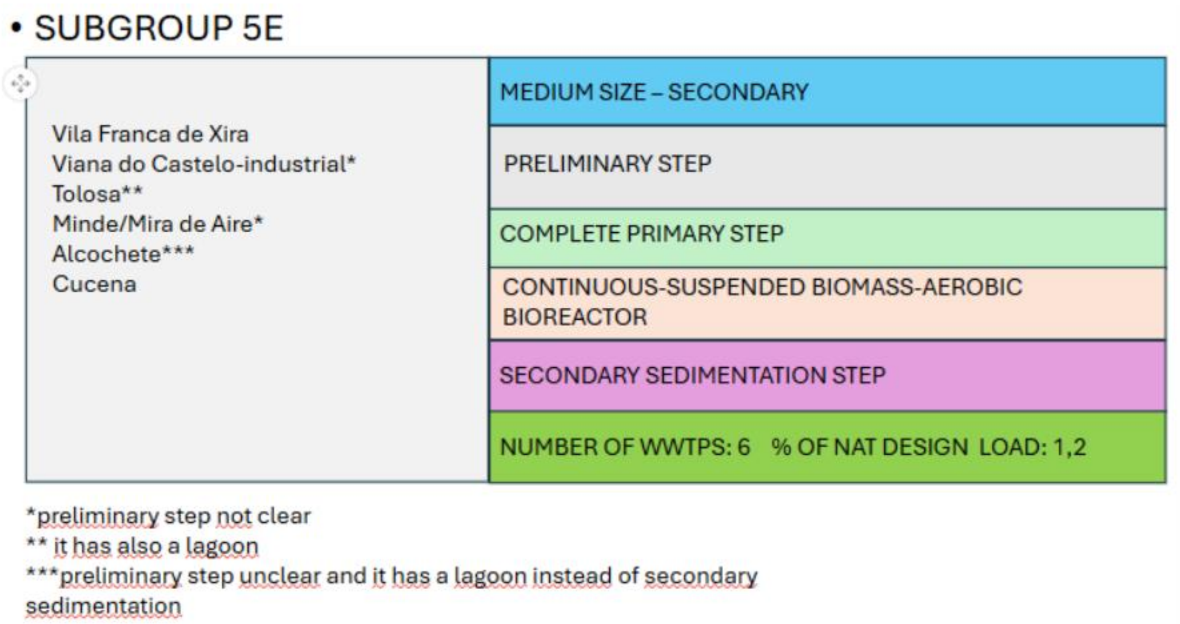


Figure 5.17: Subgroup 5E-medium size-secondary level-complete primary step-continuous-suspended biomass-aerobic bioreactor

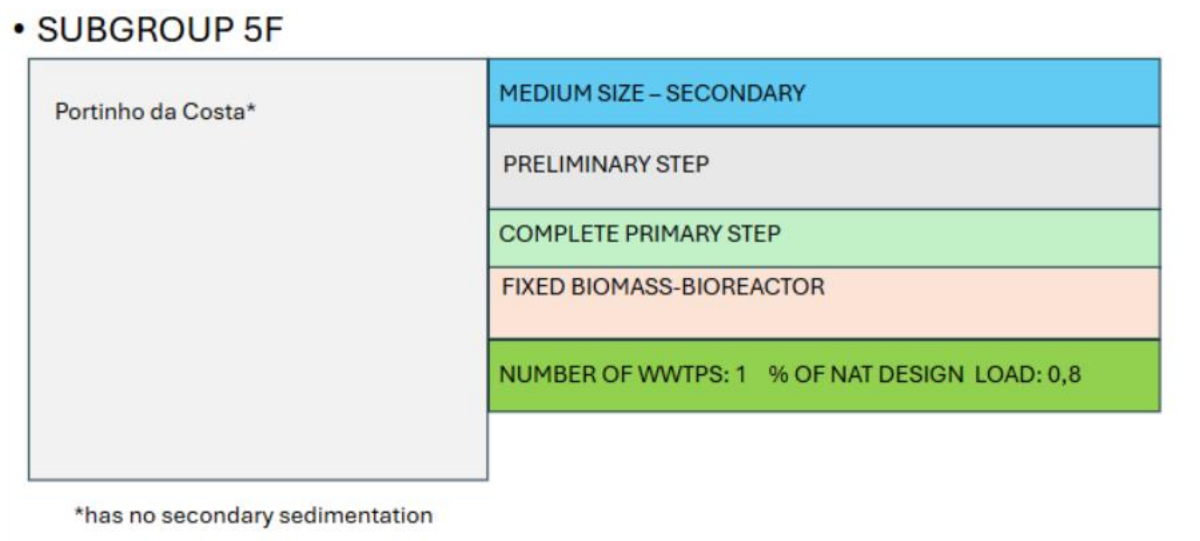


Figure 5.18: Subgroup 5F-medium size-secondary level-complete primary step-fixed biomass-bioreactor

- SUBGROUP 5G

Fernao Ferro Pinhal Novo* Carregado** Palmela/Auto Europa Quinta do Conde	MEDIUM SIZE - SECONDARY
	PRELIMINARY STEP
	COMPLETE PRIMARY STEP
	CONTINUOUS-SUSPENDED BIOMASS-A/O BIOREACTOR
	SECONDARY SEDIMENTATION STEP
	NUMBER OF WWTPS: 5 % OF NAT DESIGN LOAD: 1,3

* it has no preliminary treatment and sand-grit-grease removal and it has a lagoon

** the anoxic section is separate from the aerobic reactor in the form of a UASB

Figure 5.19: Subgroup 5G-medium size-secondary level-complete primary step-continuous suspended biomass-A/O-bioreactor

- SUBGROUP 6A

Oliveira do Hospital* Palmeira Seia* Quinta do Lago*** Albufeira Poente* Portalegre Viseu Sul**	MEDIUM SIZE – NUTRIENTS REMOVAL
	PRELIMINARY STEP
	INCOMPLETE PRIMARY STEP
	CONTINUOUS-SUSPENDED BIOMASS-A/O BIOREACTOR
	SECONDARY SEDIMENTATION STEP
	NUMBER OF WWTPS: 7 % OF NAT DESIGN LOAD: 2,1

* it has chemical P precipitation

** chemical P precipitation + intermittent aeration in aerobic zone + MBR instead of secondary sedimentation

*** no info on preliminary step and primary step assumed absent. It has chemical P precipitation

Figure 5.20: Subgroup 6A-medium size-nutrients removal-incomplete primary step-continuous suspended biomass-A/O-bioreactor

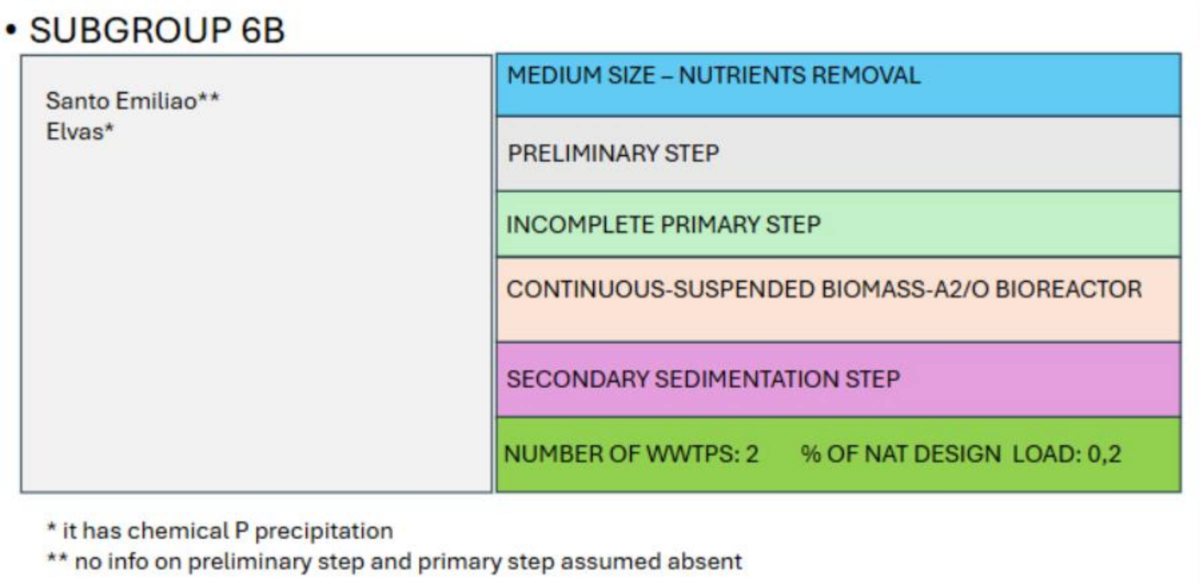


Figure 5.21: Subgroup 6B-medium size-nutrients removal-incomplete primary step-continuous suspended biomass-A2/O-bioreactor

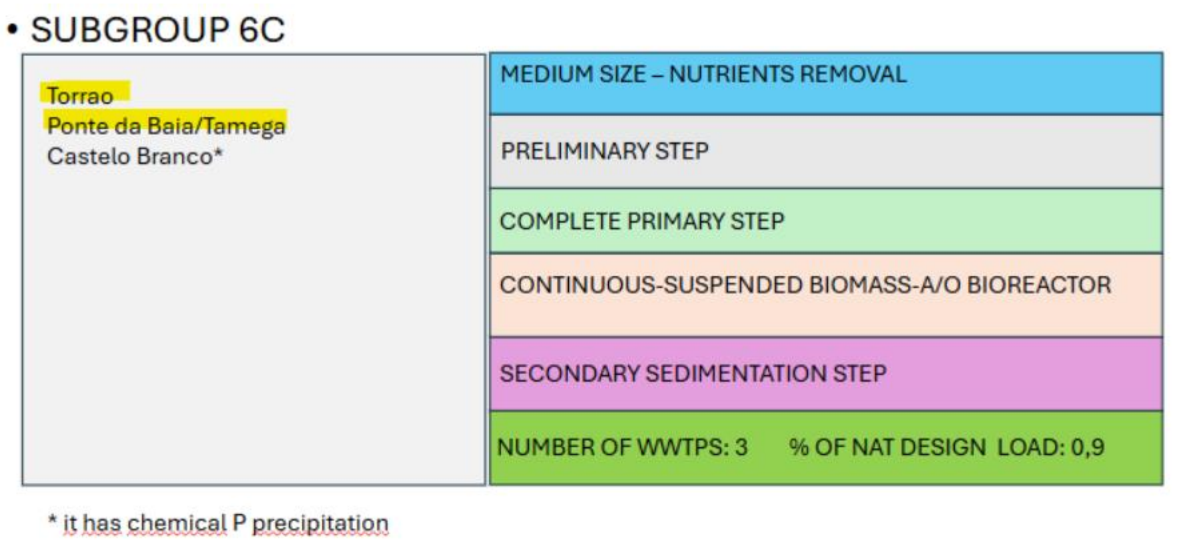


Figure 5.22: Subgroup 6C-medium size-nutrients removal-complete primary step-continuous suspended biomass-A/O-bioreactor

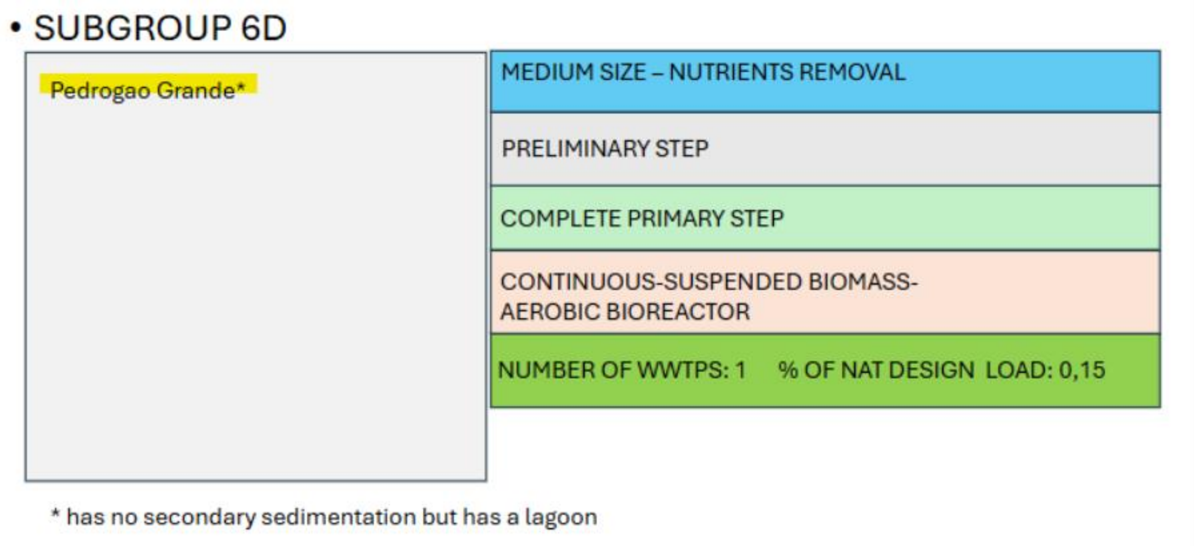


Figure 5.23: Subgroup 6D-medium size-nutrients removal-complete primary step-continuous suspended biomass-aerobic-bioreactor

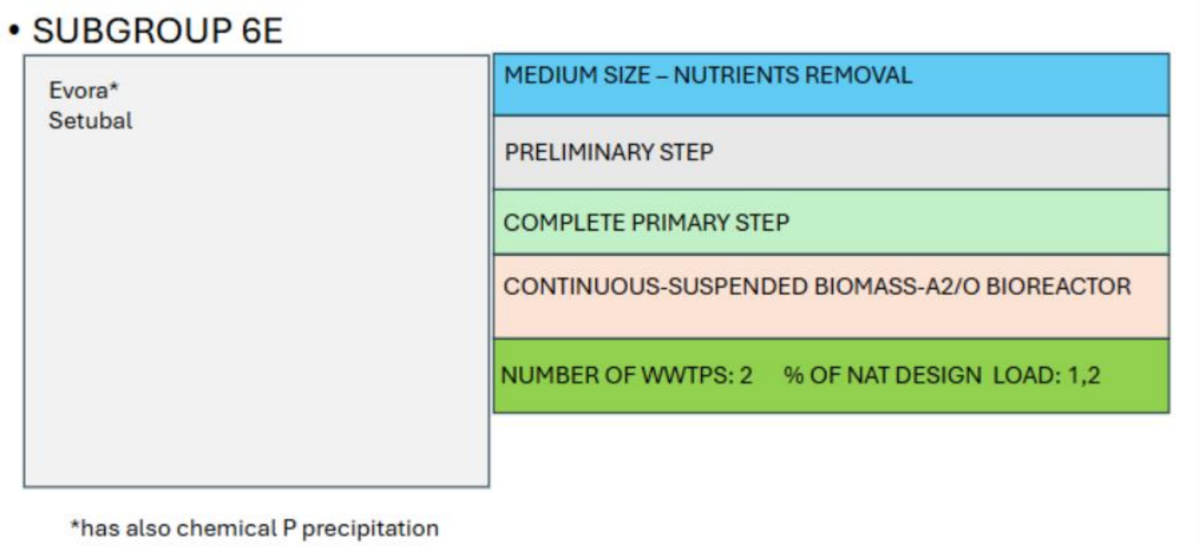


Figure 5.24: Subgroup 6E-medium size-nutrients removal-complete primary step-continuous suspended biomass-A2/O-bioreactor

5.3 Identification of the most relevant subgroups of WWTPs to retrofit

Having concluded the clustering, the amount of subgroups identified is not small. However, as already specified, the goal of the clustering is to target the most common starting configurations for the Portuguese WWTPs that must be retrofitted to enhance their nutrients removal performances.

Some subgroups, such as SBR or fixed biomass bioreactors, represent a very limited number of situations. For the following parts of the work these subgroups will be excluded not representing common starting configurations.

The next chapters of the work will focus on providing strategies to retrofit the subgroups included in Table 5-6. These subgroups, overlooking for a moment the completeness of the primary step, consist of primary level WWTPs and of WWTPs possessing continuous-suspended-biomass reactors, either with only aerobic zones or with anaerobic/anoxic/aerobic sections.

As reported in Table 5-5 they do represent a large share, both of the total number of WWTPs that must by law be retrofitted, and of the national design capacity.

Table 5-5: WWTPs for which nutrients removal retrofitting strategies will be suggested

FINAL FOCUS	(Total number of WWTPs to retrofit by law: 108)
nr of WWTPs	68
% of national design load dealt with in focus subgroups	54,78

The retrofitting strategies will need to be shaped based on the presence of a full/incomplete primary step, variety of zones present in the bioreactor, and secondary sedimentation unit presence/absence, but, despite these factors, the WWTPs belonging to Table 5-6, apart the primary ones, can be initially considered as sharing a common starting situation due to the nature of their bioreactor.

Table 5-6: Final focus subgroups

	SUBGROUPS FOR WHICH RETROFITTING STRATEGIES WILL BE SUGGESTED
SUBGROUP 1	Big size-primary level-complete primary step
SUBGROUP 2.A	Big size-secondary level-incomplete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 2.B	Big size-secondary level-complete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 2.C	Big size-secondary level-complete primary step-continuous suspended biomass bioreactor-aerobic only
SUBGROUP 2.E	Big size-secondary level-complete primary step-continuous suspended biomass bioreactor-A2/O
SUBGROUP 3.A	Big size-nutrients removal-incomplete primary step-continuous suspended biomass bioreactor-A2/O
SUBGROUP 3.B	Big size-nutrients removal-complete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 4.B	Mid size-primary level-complete primary step-continuous suspended biomass bioreactor
SUBGROUP 4.D	Mid size-primary level-complete primary step
SUBGROUP 5.A	Mid size-secondary level-incomplete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 5.B	Mid size-secondary level-incomplete primary step-continuous suspended biomass bioreactor-A2/O

SUBGROUP 5.D	Mid size-secondary level-incomplete primary step-continuous suspended biomass bioreactor-aerobic only
SUBGROUP 5.E	Mid size-secondary level-complete primary step-continuous suspended biomass bioreactor-aerobic only
SUBGROUP 5.G	Mid size-secondary level-complete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 6.A	Mid size-nutrients removal-incomplete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 6.B	Mid size-nutrients removal-incomplete primary step-continuous suspended biomass bioreactor-A2/O
SUBGROUP 6.C	Mid size-nutrients removal-complete primary step-continuous suspended biomass bioreactor-A/O
SUBGROUP 6.D	Mid size-nutrients removal-complete primary step-continuous suspended biomass bioreactor-aerobic only
SUBGROUP 6.E	Mid size-nutrients removal-complete primary step-continuous suspended biomass bioreactor-A2/O

5.4 Average performances of Portuguese WWTPs that need retrofit

During the web search for the water line schemes of the Portuguese WWTPs included in the priority groups it was occasionally possible to retrieve information on the treated volume and the nutrients influent and discharged loads. In a few exceptional cases this information on influent and discharged loads was already present in the EU dataset as ordinarily happened in the Danish case.

Effluent composition in terms of (COD, BOD, TN, TP) was computed in those cases together with removal performances.

Uncommon but not impossible was the finding of energy consumption and sludge generation for some of these Portuguese WWTPs to retrofit.

For what concerns chemicals consumption the few cases where data were available mentioned mostly chemicals linked to sludge dewatering neglecting all the chemicals used in the water line. For this reason it was not possible to estimate directly chemicals consumption for Portuguese WWTPs.

Biogas generation was another parameter not easy to find, and retrievable on a very limited number of occasions.

Land area occupied by the WWTPs was seldomly found

Despite the difficulties, specific values of energy consumption and sludge generation per m3 treated were computed when available.

Various LCA studies already stated that, to better get the effect of the interventions in terms of nutrients removal, WWTPs performances should be studied in terms of kg of nutrients and organic matter removed, rather than in terms of volume of raw wastewater treated. (Garcia et al., 2011)

Knowing this the analysis was repeated on a kg of nutrients removed basis when possible.

Land area occupation was related to the nominal size of the WWTPs and expressed in (m2/pe) to have it independent from a time basis.

Biogas generation heavily relies on infrastructures belonging to the sludge line, which has been almost always treated as a black box throughout the all work.

Nevertheless, depending substantially on the fraction of the COD load subtracted to BNR processes with primary sludges, biogas generation was equally included in the analysis.

Portuguese WWTPs already adopting anaerobic sludges digestion and retrofitting their process scheme to divert less C from the water line to have it available for BNR processes might see a reduction of biogas production if no other strategy is implemented.

Knowing this, performances derived from EU dataset and web review for Portuguese WWTPs belonging to the priority list are presented in Table 5-7. To contextualize the results, national, regional or multiple Portuguese WWTPs studies available in literature were showed too in Table 5-8, Table 5-9 and Table 5-10.

Results for Portuguese WWTPs subdivided in key subgroups or merged key subgroups were not extracted being the sample size already limited considering all the data available. To highlight how the nominal level of treatment and size class affect the performances there is the need to acquire more data than those now available to compute reasonable averages.

Table 5-7: Average performances of same of the Portuguese WWTPs to retrofit belonging to the priority list

AVERAGES	Portuguese WWTPs To retrofit
effluent TN (mg/L) – sample of 31 WWTPs	27,98
effluent TP (mg/L) – sample of 29 WWTPs	2,88
effluent COD (mg/L) – sample of 33 WWTPs	60,58
effluent BOD (mg/L) – sample of 32 WWTPs	12,15
TN % removal– sample of 13 WWTPs	65,88
TP % removal– sample of 10 WWTPs	74,28
COD % removal– sample of 15 WWTPs	90,63
BOD % removal– sample of 14 WWTPs	93,84
energy consumption (kWh/m3) – sample of 10 WWTPs	0,80
energy consumption (kWh/kg N removed) – sample of 5 WWTPs	11,75
energy consumption (kWh/kg P removed) – sample of 3 WWTPs	57,22
Dry sludge production (kg/m3) – sample of 10 WWTPs	1,09
Dry sludge production (kg/kg N removed) – sample of 4 WWTPs	40,18
Dry sludge production (kg/kg P removed) – sample of 2 WWTPs	312,14
energy produced from biogas (kWh/m3 treated) – sample of 2 WWTPs	0,41
energy produced from biogas (kWh/kg N removed) – sample of 1 WWTPs	2,42

energy produced from biogas (kWh/kg P removed) – sample of 1 WWTPs	14,72
Land requirements (m2/pe design capacity) – sample of 4 WWTPs	0,12

Table 5-8: Energy consumption of Portuguese WWTPs (Silva, Rosa, 2015)

	n of wwtps	kWh/m3 treated	kWh/kg BOD removed	kWh/kg COD removed
AS systems without primary sedimentation P25-P75		0,72-1,34		
AS systems with primary sedimentation P25-P75		0,31-0,84	0,3-8,25	
AS systems with primary sedimentation avg			2,96	
biofilters avg		0,79		
rock trickling filters avg		0,16		

Table 5-9: North Portuguese WWTPs average energy consumption (Cardoso et al., 2019)

WWTP size range (pe)	n of wwtps	kWh/m3 treated	kWh/kg BOD removed	kWh/kg COD removed
2000-9999	3	0,74	2,09	1,1
10000-49999	13	1,39	2,03	1,19
>50000	4	0,73	1,67	1,12
WWTP size range (m3/d)	n of wwtps	kWh/m3 treated	kWh/kg BOD removed	kWh/kg COD removed
<1370	7	1,93	2,42	1,32
1370-4110	8	0,75	1,67	1,07
>4110	5	0,74	1,8	1,1
WWTP primary treatment	n of wwtps	kWh/m3 treated	kWh/kg BOD removed	kWh/kg COD removed
no	14	1,42	2,31	1,35
yes	6	0,56	1,16	0,73

Table 5-10: Portuguese WWTPs Biogas specific production (Silva, Rosa, 2015)

	(kWh/m3 treated)
biogas energy production literature	0,074-0,15
biogas energy production computed	0,074-0,389
biogas energy production measured	0,12-0,25

Starting from the general results available in Table 5-7 for the Portuguese WWTPs to retrofit whose data were found, these are the main conclusions:

- Presented results reveal a good accordance with other Portuguese studies for what concerns energy consumption (Table 5-8, Table 5-9)
- For biogas production the results are less in agreement with previous Portuguese studies. In fact, energy production through biogas seems higher than typical Table 5-10.

- Regarding effluent composition, sludge generation and land requirements no other Portuguese study was available.

5.5 Chapter Summary and Key Findings

- 98 out of the initial 108 WWTPs to retrofit were considered a priority initially excluding 10 medium WWTPs possessing at least one between N or P removal steps
- 68 out of the 98 priority WWTPs were included in the group of interest after the clustering based on the shared water line features, either because of lacking a secondary treatment step, or because possessing it in the form of a continuous suspended biomass bioreactor
- The share of the national design treatment capacity of the 68 WWTPs of interest is around 55%
- The average performances extracted from the results available for the 68 WWTPs of interested proved the present poor nutrients removal level with TN and TP concentrations in the effluent far above 20 and 2 mg/L and percentages removal below 75%.

6 Analysis of Danish Reference WWTPs for Nutrient Removal

As a result of the previous chapter, the focus of the analysis is now narrowed to Portuguese WWTPs that achieve just a primary level, or that possess a continuous, suspended-biomass-bioreactor preceded by a complete/incomplete primary step.

The goal is to suggest retrofitting strategies for these WWTPs to let them reach the targets required for nutrients removal.

Since the most common Portuguese WWTPs' bioreactor configuration is based on continuous, suspended-biomass systems, retrofitting strategies that still rely on this type of bioreactor would probably be the most suitable.

In this chapter Danish WWTPs are analysed in search of inspiring configurations to retrofit Portuguese ones. As already stated in the introductory part, Danish set the standard for wastewater treatment field. Moreover, most of the Danish WWTPs bioreactors are known to be continuous, suspended-biomass systems. (Mielczarek, 2012)

The first objective of this chapter will be to give evidence that top-Danish WWTPs already fulfil the new targets in terms of nutrients removal. This will be done, as said in **Error! Reference source not found.** section, by filtering out from the EU dataset, WWTPs that discharge effluents with N and P concentrations typically below the new limits (Table 2-2). For the top performing WWTPs a search will be done to find out which configurations these top-Danish WWTPs adopt. Light will be shed on the bioreactor's types, but attention will be given in general to the entire sequence of steps adopted. The idea is to start getting an understanding of the conditions under which, a WWTP basing its nutrients removal mainly on a continuous, suspended-biomass bioreactor, can fulfil the new targets.

To achieve this second objective an analysis of the water line of top-performing Danish WWTPs will be conducted through web research in a similar way as the one of the previous chapter.

The expected outcome of this chapter will be the identification of the most common configurations and strategies that Danish WWTPs with a continuous, suspended-biomass bioreactor, adopt to fulfil the new requirements in terms of nutrients removal.

From the 127 Danish WWTPs selected as reference, relevant information was found for 47 of them. WWTPs were clustered in 31 groups formed by WWTPs sharing almost identical water line nutrients removal steps. The water lines representative of each group are displayed in figures.

Below each figure, the specific WTTPs belonging to the group are mentioned.

As for the Portuguese case, most of the treatment schemes found on the web date back to more than 10 years ago. It's very likely that Danish plants upgraded their schemes in the meanwhile. Additionally, the sources may not always be complete.

6.1 Selection of Reference WWTPs

Danish WWTPs above 10 000 pe design capacity, with N and P % removals respectively above 85% and 90% and N and P effluent concentrations respectively below 8 mg/L and 0,7 mg/L, were filtered out from the EU dataset to form the list of reference WWTPs.

The reason behind the choice to require minimum 85% and 90% N and P removal instead of the 80 and 87,5 % is to shorten the list of possible reference WWTPs to make the following water line web search more compact.

In the end the list was formed by 127 WWTPs

6.2 Average performances of Danish reference WWTPs

Performances for some of the reference Danish WWTPs where retrieved proceeding similarly to the case of priority Portuguese WWTPs for what concerns energy consumption, sludge production, chemicals and land demand. The main difference lied in pollutants % removal and effluent concentrations. These were in fact already computable directly from the data present in the EU dataset. Thanks to the available values for the volume treated and COD, BOD, N, and P incoming and discharge loads, columns COD, BOD, N, P % removal and effluent concentrations were computed.

The results are presented in Table 6-1. Again, no presentation of data subdivided according to macro families of WWTPs will be done being the size of the total sample available too limited

Table 6-1: Average performances for some of Danish reference WWTPs

Averages for Danish reference WWTPs	
N effluent (mg/L) - 47 WWTPs sample size	3,6
P effluent (mg/L) - 47 WWTPs sample size	0,3
effluent COD (mg/L) - 47 WWTPs sample size	28,4
effluent BOD (mg/L) - 47 WWTPs sample size	2,5
N % removal- 47 WWTPs sample size	92,8
P % removal- 47 WWTPs sample size	95,0
COD % removal- 47 WWTPs sample size	95,4
BOD % removal- 47 WWTPs sample size	98,9
Energy consumption (kWh/m3) - 8 WWTPs sample size	0,54
energy consumption (kWh/kg N removed) - 8 WWTPs sample size	11,61
energy consumption (kWh/kg P removed) - 8 WWTPs sample size	82,40
Chemicals consumption (kg/m3) - 2 WWTPs sample size	0,048
chemicals consumption (kg/kg N removed) - 2 WWTPs sample size	1,04
chemicals consumption (kg/kg P removed) - 2 WWTPs sample size	7,36
Dry Sludge production (kg/m3) - 8 WWTPs sample size	0,90
Dry sludge production (kg/kg N removed) - 8 WWTPs sample size	19,41
Dry sludge production (kg/kg P removed) - 8 WWTPs sample size	137,74
Land requirements (m2/pe) - 2 WWTPs sample size	0,4

Since too little sample size was available, DANVA report was used to complement some estimates.

Table 6-2: Danish Wastewater sector effluent averages (DANVA, 2025)

DENMARK	
% of separate sewer system	71,9
separate sewers bringing wastewater to WWTP	
Average BOD treated wastewater outlet concentration (mg/L)	5,6
Average N treated wastewater outlet concentration (mg/L)	1,9
Average P treated wastewater outlet concentration (mg/L)	0,25

Combined sewers bringing wastewater to WWTP	
Average BOD treated wastewater outlet concentration (mg/L)	39,3
Average N treated wastewater outlet concentration (mg/L)	13,1
Average P treated wastewater outlet concentration (mg/L)	2,1
dry solids production (kg/m3 wastewater treated)	0,23

Table 6-2 reports substantially lower sludge production with respect to the results coming from the web search for the water lines scheme. Probably the values reported by DANVA are more trustable. It must be said moreover that they originate from a wider sample including WWTPs not present in the reference list used in this work. Effluent composition differs significantly according to the nature of the sewer network connected to the WWTP. The kind of sewer seems to be the most relevant factor in determining the effluent quality, more than the treatment scheme adopted at the WWTP.

The very high share of separate sewer networks is a key point of the Danish model that throughout this work has not been evidenced since modifying the sewers implies large structural interventions on a national scale. This kind of strategy probably requires a greater effort compared to acting on isolated WWTPs modifying their treatment scheme. However, it’s clear that Danish strategy prioritizing large investments on the sewer network rather than on the (already efficient) WWTPs is working (Table 6-3).

Again, as for sludge generation, the electricity consumption performance reported in Table 6-4 is better than what found with the web search. Probably this is also because the WWTPs the reference list was made of were the ones achieving the best removal performances and thus probably requiring higher energy consumption than the national average. Unfortunately, no value was found for chemicals and land requirements.

Table 6-3: Danish wastewater sector average costs and investments 2010-2024 (DANVA, 2025)

AVERAGE COSTS AND INVESTMENTS	
wastewater utilities operating cost (euros/m3 treated) 2010-2024	1,79-2,14
wastewater operating costs % on sewage network	33
wastewater operating costs % on plants	48
wastewater operating costs % on customer service	5
wastewater operating costs % on general adminstration	14
wastewater utilities investment costs (euros/m3 treated) 2010-2024	2,33-4,35
wastewater investment costs % on sewage network	82
wastewater investment costs % on plants	14
wastewater investment costs % on the rest	4

No specific info was derived on energy production from biogas but information on energy self-sufficiency was available instead (Table 6-4).

Table 6-4: Danish wastewater sector average heat and electricity balances (DANVA, 2025)

HEAT AND ENERGY BALANCE	
Total specific energy consumption for wastewater transport to WWTPs (kWh/m3)	0,16
Total specific heat consumption for wastewater transport to WWTPs (kWh/m3)	0,004
Total specific energy consumption for wastewater treatment in WWTPs (kWh/m3)	0,35
Total specific heat consumption for wastewater treatment in WWTPs (kWh/m3)	0,12
total % electricity self sufficiency (self produced and used for transport+treatment + sold)	17,19
total % heat self sufficiency (self produced and used for transport+treatment + sold)	222,22

6.3 Treatment Configurations

Danish reference WWTPs have been categorized in subgroups depending on the treatment steps present in their water lines. In Table 6-5 a legend is given to understand

Table 6-6 where Danish reference WWTPs are subdivided in groups sharing common water line structure.

Table 6-5: Water line treatment steps and auxiliary strategies identification codes

TREATMENT STEP OR AUXILIARY STRATEGY	ID
Preliminary screening and sieving	PSS
Sand grit and grease tanks	SGG
Primary coagulation-flocculation separate tanks	PCF
Storm water storage tanks	SW
Sedipac primary tanks/Multiflow/actiflow-Compact primary treatment steps	CPT
equalization tanks	EQ
Salsnes filter for C harvest	SF
Primary sedimentation tanks	PST
Continuous suspended biomass-A/O + BAF	A/O + BAF
Continuous suspended biomass-A/O	A/O
Continuous suspended biomass-A2/O	A2/O
Continuous suspended biomass-A2/O + BAF	A2/O + BAF
Granular sludge Recycle technology to improve settleability	GS
Activated return sludge (to improve sludge settleability and reduce excess sludge production)	ARS
secondary sedimentation tanks	SST
raw influent fermentation to prepare it for EBPR	RIF
Recycled sludges fermentation to prepare EBPR	RSF
Extra C source dosing for denitrification step	Extra C
Intermittent aeration in aerobic tanks (no need of specific anoxic tanks)	IA
Chemicals dosing for P precipitation	CP
recycled reject water from sludge line fermentation to prepare influent for EBPR	RRW
side stream NH4 removal step on liquors recycled from sludge line back to water line	SNH4
Polyelectrolyte dosing for coagulation/flocculation	PYCF

Final reaeration	FR
online sensors connected to a SCADA for extensive automation and online control	SCADA
Digital twin model of the WWTP	DT

Table 6-6: Subgroups of reference Danish WWTPs

DK REFERENCE WWTPS SUBGROUP	1	2	3	4	5	6	7	8
WWTPS	Lynetten	Avedore	Niva	Aalborg west	Skagen	Viby	Korsor	Slagelse
PSS	1	1	1	1	1	1	1	1
SGG	1	1	1	1	1	1	1	1
PCF	1							
CPT								
SW								
EQ								
SF								
PST	1	1	1	1	1	1	1	1
A/O + BAF								
A/O						1	1	1
A2/O	1	1	1	1	1			
A2/O + BAF								
GS				1		1		
SST		1	1	1	1	1	1	1
RSF		1						
ARS								1
RIF								
RRW								
Extra C	1					1		
IA	1	1	1	1	1	1	1	1
CP	1	1	1	1	1	1	1	1
SNH4								
PYCF								
FR			1					
SCADA	1	1	1	1	1	1	1	1
DT	1	1				1		1

Table 6.7 continued

DK REFERENCE WWTPS SUBGROUP	9
WWTPS	Ringkobing; Nr. Aby; Northwest; Northeast; Otterup; Ringe; Christiansfeld; Haderslev; Himmark; Tarm
PSS	1
SGG	1
PCF	
CPT	
SW	
EQ	
SF	
PST	1
A/O + BAF	
A/O	1
A2/O	
A2/O + BAF	
GS	
SST	1
RSF	
ARS	
RIF	
RRW	
Extra C	
IA	1
CP	1
SNH4	
PYCF	
FR	
SCADA	
DT	

Table 6.7 continued

DK REFERENCE WWTPS SUBGROUP	10	11	12	13	14	15	16	17	18
WWTPS	Frederikshavn	Stavnsholt	Koge-Egnens	Esbjerg west	Damhusaen	Kolding Central	Mariagerfjord	Marselisborg	Aalborg East
PSS	1	1	1	1	1	1	1	1	1
SGG	1	1	1	1	1	1	1	1	1
PCF									
CPT									
SW			1	1		1		1	1
EQ			1	1	1	1	1		
SF									
PST	1	1	1	1	1	1	1	1	1
A/O + BAF	1	1							
A/O			1	1	1				
A2/O						1	1	1	1
A2/O + BAF									
GS									
SST	1	1	1	1	1	1	1	1	1
RSF					1				
ARS									
RIF									
RRW									1
Extra C	1								
IA	1	1	1	1	1	1	1	1	1
CP	1	1	1	1	1	1	1	1	1
SNH4								1	
PYCF									
FR									
SCADA	1		1		1			1	
DT			1		1				

Table 6.7 continued

DK REFERENCE WWTPS SUBGROUP	19	20	21	22	23	24	25
WWTPS	Ejby Molle	Fredericia	Lillerod	Naestved	Skanderborg	Bjergmarken	Ronne
PSS	1	1	1	1	1	1	1
SGG	1	1	1	1	1	1	1
PCF							
CPT							
SW	1	1	1	1	1		
EQ							
SF							
PST	1	1					
A/O + BAF							
A/O			1	1			
A2/O		1			1	1	1
A2/O + BAF	1						
GS							
SST	1	1	1	1	1	1	1
RSF							
ARS							
RIF							
RRW							
Extra C							
IA	1	1	1	1	1		1
CP	1	1	1		1	1	1
SNH4	1						
PYCF	1	1					
FR	1			1			
SCADA	1	1			1		1
DT							1

Table 6.7 continued

DK REFERENCE WWTPS SUBGROUP	26
WWTPS	Stroby; Farevejle; Soro Central; Egebjerg Sud; Strandgarden; Sonderso; Hvide Sande
PSS	1
SGG	1
PCF	
CPT	
SW	
EQ	
SF	
PST	
A/O + BAF	
A/O	1
A2/O	
A2/O + BAF	
GS	
SST	1
RSF	
ARS	
RIF	
RRW	
Extra C	
IA	1
CP	1
SNH4	
PYCF	
FR	
SCADA	
DT	

Table 6.7 continued

DK REFERENCE	27	28	29	30	31

WWTPS SUBGROUP					
WWTPS	Rundkobing; Egsmade	HCR Sud	Ega	Grindsted	Holstebro
PSS	1	1	1		
SGG	1	1	1		
PCF					
CPT				1	
SW				1	
EQ				1	
SF		1	1		
PST					1
A/O + BAF					
A/O	1				1
A2/O		1	1	1	
A2/O + BAF					
GS					
SST		1	1	1	1
RSF					
ARS					
RIF			1		
RRW					
Extra C					
IA	1	1		1	1
CP	1	1	1	1	1
SNH4		1	1	1	1
PYCF		1	1		
FR			1		
SCADA			1	1	
DT				1	

6.4 Key Nutrient Removal Strategies

From

Table 6-6 it's possible to start deriving the most common combinations of strategies Danish adopt on the water line to target nutrients removal.

For what concerns the bioreactor typically two options are preferred:

Continuous suspended biomass A/O + chemical P removal

Continuous suspended biomass A2/O (sometimes with the anaerobic section in a different tank from the tanks with anoxic and aerobic zones)

In some isolated cases, aerated biofilters (BAF) and membranes systems are coupled to the continuous suspended biomass reactors, working in parallel or in series but never completely substituting them. (membranes if present carry out filtration functions which have been omitted in the schemes)

Even playing the major role, bioreactors alone cannot be enough to reach the great performances documented. Some of the auxiliary strategies, that, in many cases play a crucial role in the effectiveness of the global removal process, and drove the clustering process, are highlighted:

Regarding N removal, the presence of anoxic zones, whether in specific tanks or implementing intermittent aeration in aerobic tanks, is sometimes coupled with external C source dosing.

Some plants lower the N load on the main line targeting the recirculated reject waters from the sludge line through anammox based processes.

For what concerns P removal, almost all plants have the possibility to dose chemicals for P precipitation even if designed as A2/O, and most of them complete the Biological removal with the chemical one.

Aeration in the aerobic compartment of the bioreactor is almost always intermittent, avoiding prolonged oxygenation periods favoring the preservation of anoxic and anaerobic zones in the close compartments.

Fermentation, either of the raw influent or of the recycled sludges, and hydrolysis tanks, are often used to enrich the stream fed to the bioreactor of VFA, essential for the success of the EBPR step.

On the recycled activated sludges, a supplemental aeration process (ARP), leading also to increased endogenous respiration phenomena, that lower sludge volumes, is sometimes performed.

In some isolated cases, a selection of the fastest settling sludge granules is made prior to the recycling to build a granular sludge in the bio reactor.

Almost all the studied Danish WWTPs possess an high level of automation due to a fleet of accurate online measuring sensors and actuators connected to a SCADA system. Operators can rely heavily on the SCADA system thanks to the frequent maintenance work to which sensors are subject to.

Primary sedimentation tanks play a strategical role in lowering the organic load to the biological reactors, that might be useful in terms of aeration requirements but may be counterproductive in terms of C/N and C/P ratios for biological nutrients removal. Additionally, these tanks possess a substantial volume that could be partly destined to biological processes in reconversion and retrofitting strategies. For these reasons the presence/absence of primary sedimentation tanks, or the presence of compact systems or salsnes filter was chosen as a clue parameter in the clustering process.

Primary coagulation-flocculation and filtration steps impact heavily the lowering of the C load sent to the bioreactor affecting the nutrients bio removal processes. On the other hand they contribute to suspended solids removal, constituted also of chemically precipitated P. This led to the inclusion of these units among the relevant factors for the clustering process. For the reasons of high land area demand, and through repurposing, potential extra biologically reactive volume availability, also secondary sedimentation step presence/absence was considered in the clustering process.

Lastly, among the factors included in the clustering process, there were also equalization tanks and storm water retention basins, which contribute to the homogenization of the conditions under which the bioreactors operate. Bioreactor operations benefit greatly of stable conditions.

The digital twin presence instead, has been overlooked in the clustering process. Danish in some cases developed models, digital twins of the WWTPs, that are used for the testing of alternative operative strategies prior to the direct implementation. However, being something more helpful in the case of the testing of future possible strategies, rather than in the direct improvement of the process operation, these have not been considered for the clustering.

After having quickly identified the main strategies adopted in the reference Danish contexts, the next chapter will give a more detailed study of the factors that determine the feasibility of implementing some combinations of these strategies, in the most common starting configurations of the Portuguese WWTPs needing retrofit for enhanced nutrients removal.

6.5 Relevance for Portuguese Context

The focus of this chapter will be on highlighting some of the performance changes that the implementation of the Danish system would bring about in Portuguese WWTPs.

This will be done by comparing the performances of the reference Danish plants, ideally considered representatives of the Portuguese ones, once retrofitted, with the present performances of the Portuguese plants found on the web.

The comparison is obviously very rough and doesn't claim to be considered rigorous. It is however useful to have a visualization of at least the order of magnitude of some of the changes that would happen if Portuguese WWTPs switched to continuous, suspended biomass, BNR systems.

The comparison is based on the results reported in Table 5-7 and Table 6-1, from where what emerges is that Danish removal performances and effluent quality seem considerably better, despite the lower energy consumption with respect to Portuguese one. Sludge production is lower while land requirements are higher than Portuguese ones. To help the reader visualize the differences figures will compare separately different performance categories extracted from the tables.

Since results will be reported not only on a treated volume basis, but also on a mass of nutrients removed basis, strange behaviours may be observed.

These could be due to the very limited size of the samples for what concerns energy consumption and sludge production. Moreover, WWTPs for which sludge information was available, are not always also the WWTPs for which energy information was found, and vice versa.

For this reason, when comparing results on a mass basis of nutrients removed, energy patterns may seem in contrast with sludge ones. However, a possible explanation for these contrasting trends is that the mass of nutrients removed by the Danish WWTPs for which energy data were found, is lower than the one removed by Portuguese WWTPs with energy data available.

The contrary happens in the case of WWTPs with sludge production information, where the mass of nutrients removed by the Danish WWTPs for which sludge production info was found is higher than the mass of nutrients removed by Portuguese WWTPs for which sludge info was retrieved (Table 6-7).

Table 6-7: kg of N and P removed/year in those WWTPs which had data for energy and sludge

Comparison of kg removed of Nutrients for the WWTPs which had data available on sludge production and energy consumption	
Kg N removed/year in Portuguese WWTPs where energy data where available	2 351 641
Kg N removed/year in Danish WWTPs where energy data where available	2 281 391
Kg P removed/year in Portuguese WWTPs where energy data where available	343 940
Kg P removed/year in Danish WWTPs where energy data where available	332 070
Kg N removed/year in Portuguese WWTPs where sludge data where available	1 783 435
Kg N removed/year in Danish WWTPs where sludge data where available	2 126 036
Kg P removed/year in Portuguese WWTPs where sludge data where available	157 499
Kg P removed/year in Danish WWTPs where sludge data where available	325 954

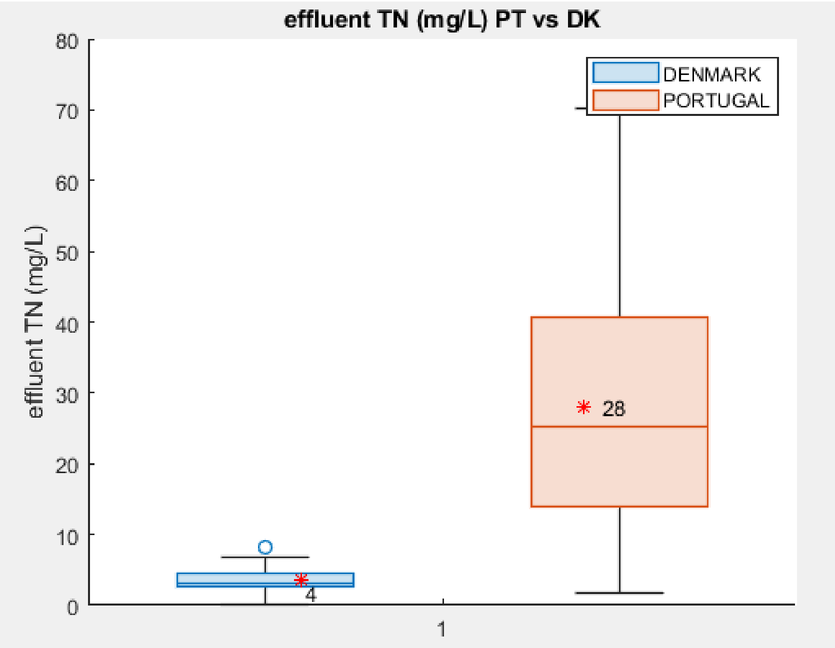


Figure 6.1:Effluent TN (mg/L), PT vs DK

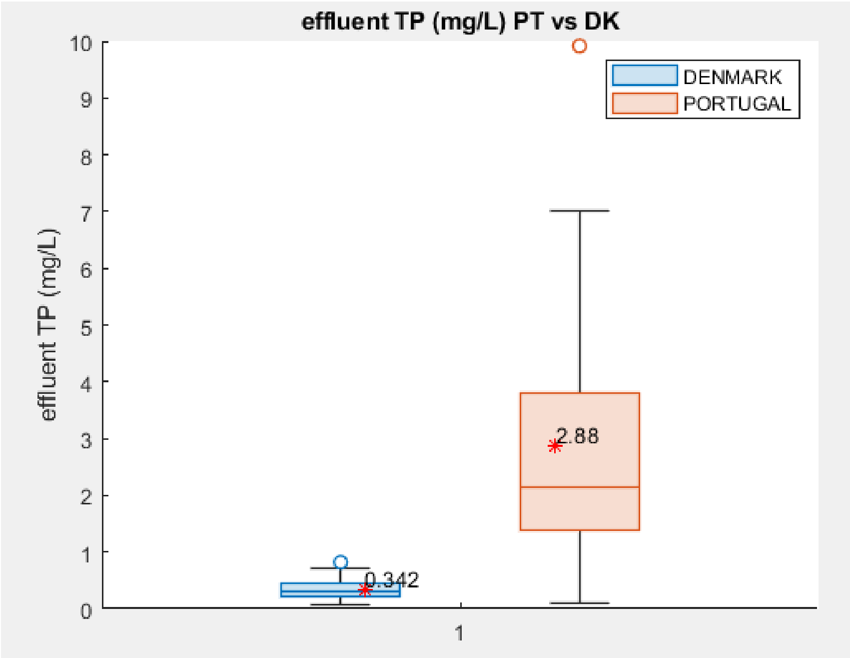


Figure 6.2: Effluent TP (mg/L), PT vs DK

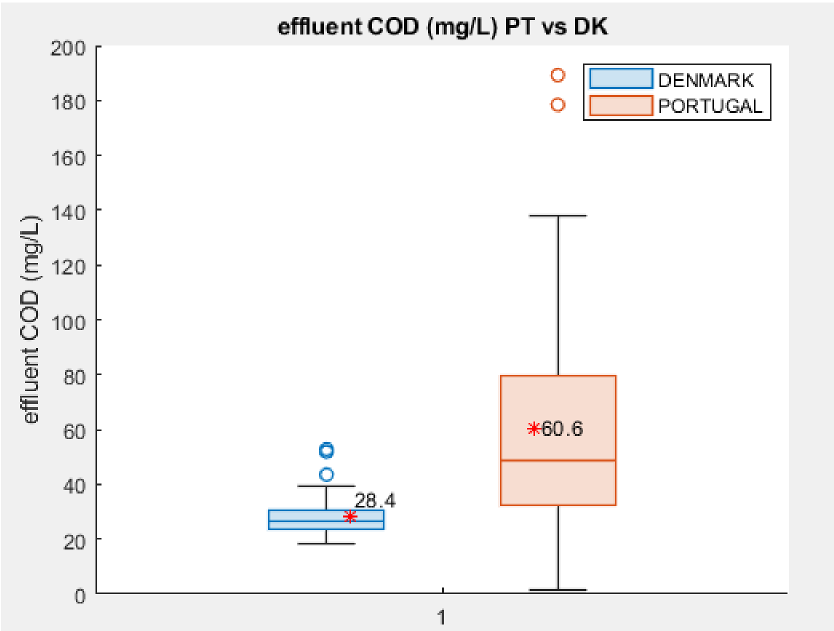


Figure 6.3: Effluent COD (mg/L), PT vs DK

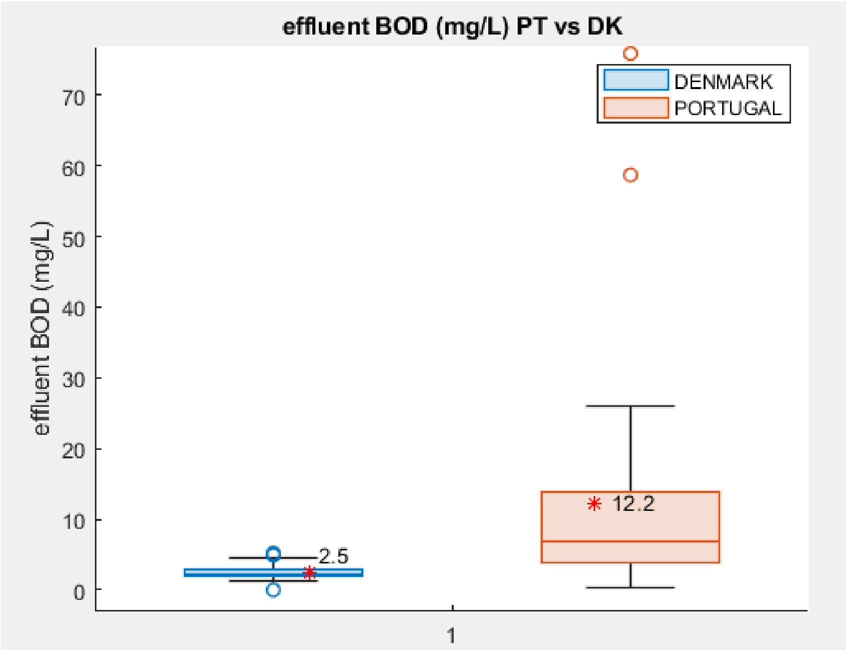


Figure 6.4: Effluent BOD (mg/L), PT vs DK

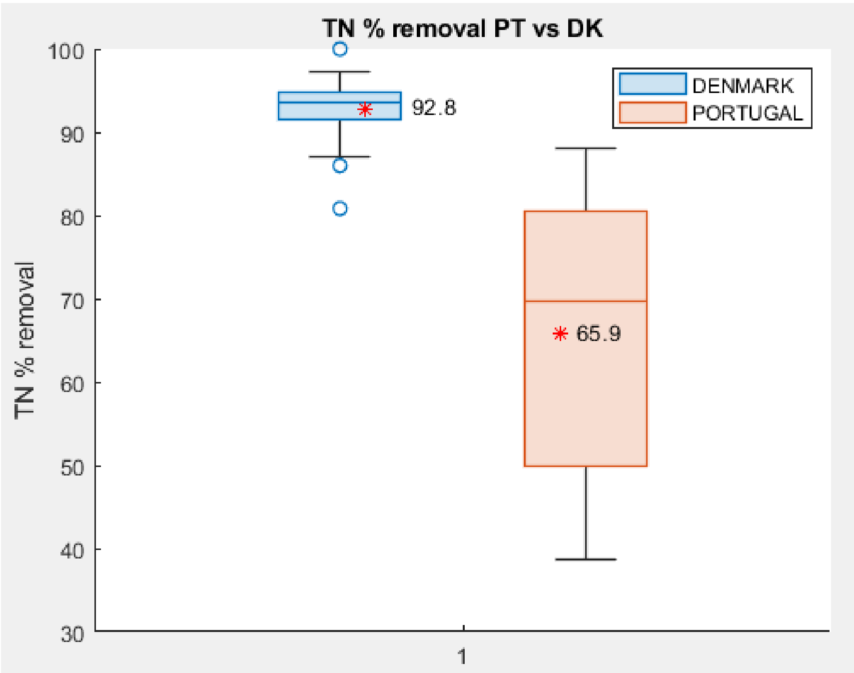


Figure 6.5: TN % removal PT VS DK

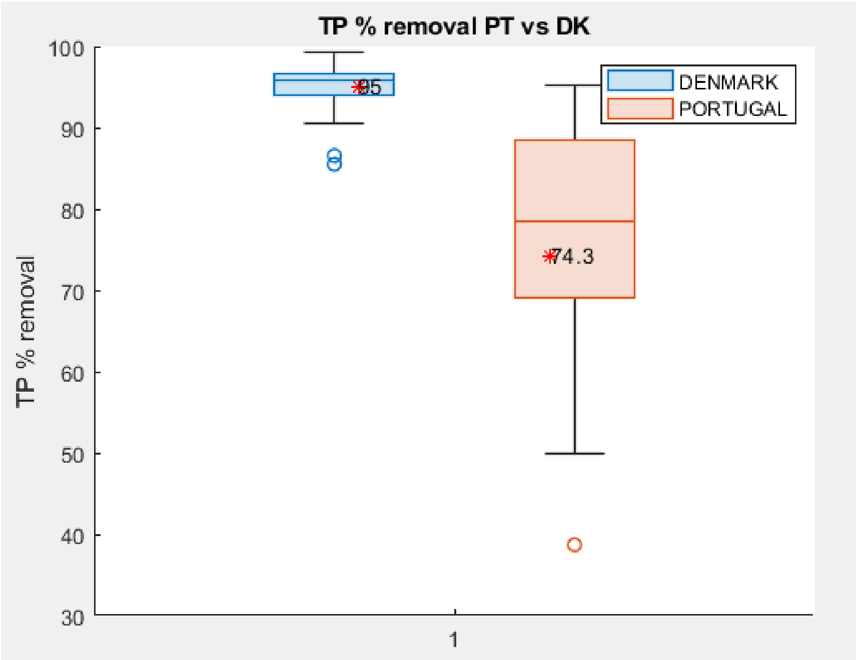


Figure 6.6: TP % removal PT VS DK

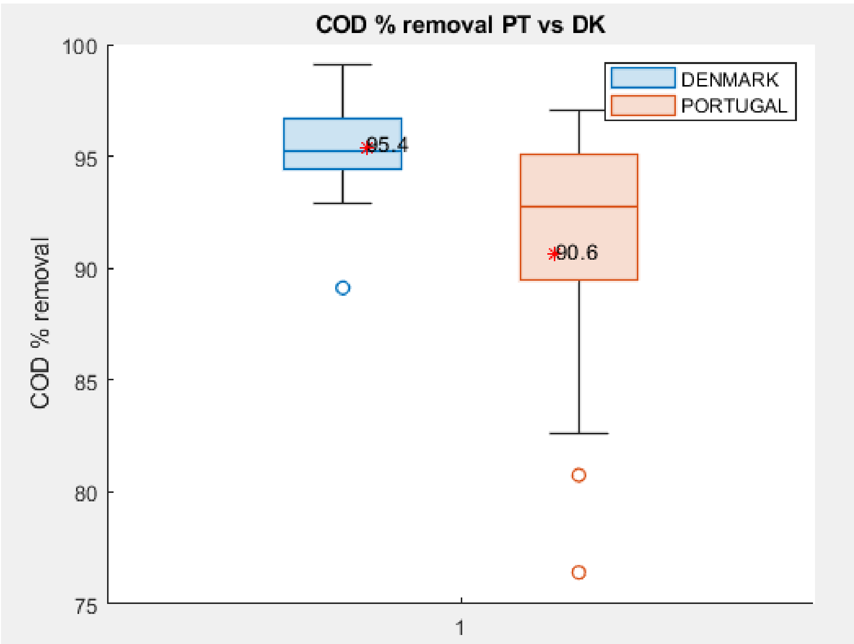


Figure 6.7: COD % removal PT VS DK

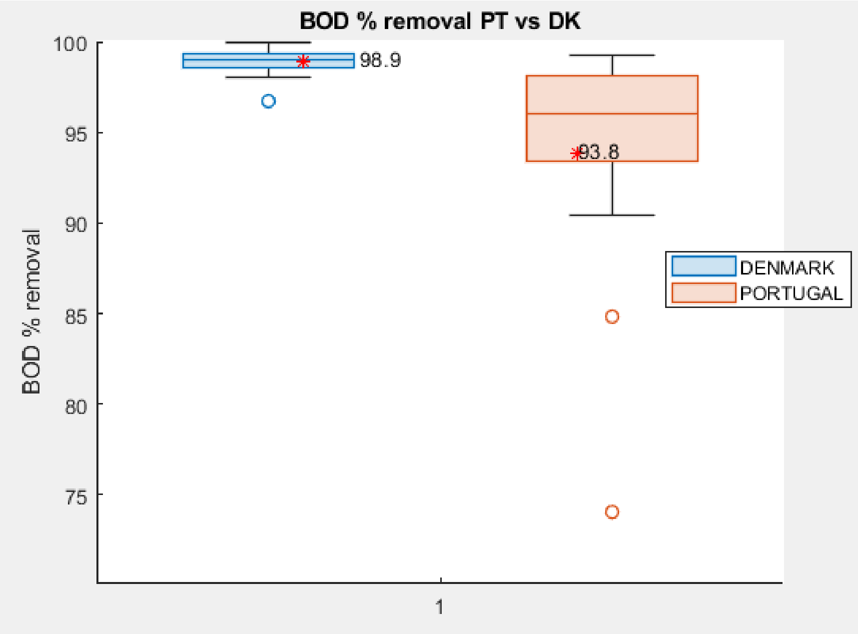


Figure 6.8: BOD % removal PT VS DK

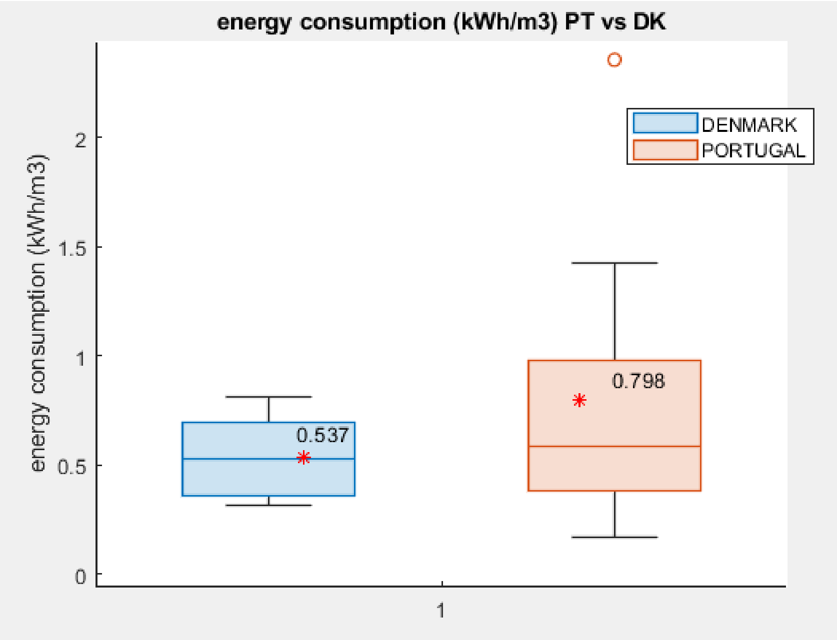


Figure 6.9: Energy consumption (kg/m3 treated) PT VS DK

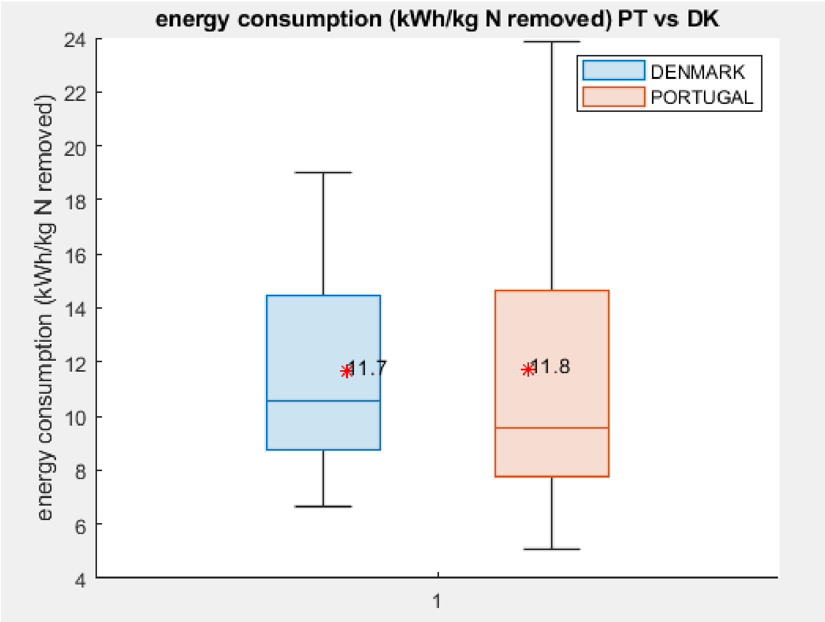


Figure 6.10: Energy consumption (kg/kg N removed) PT VS DK

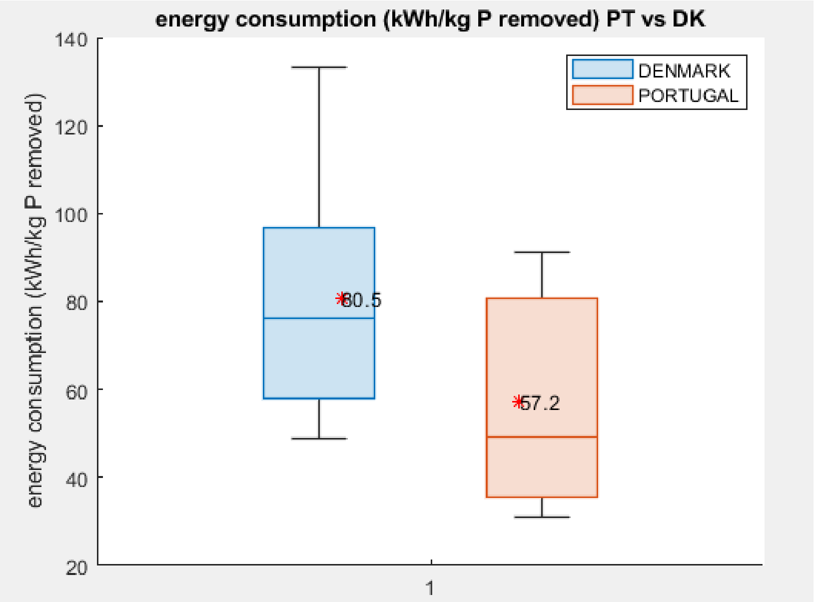


Figure 6.11: Energy consumption (kg/kg P removed) PT VS DK

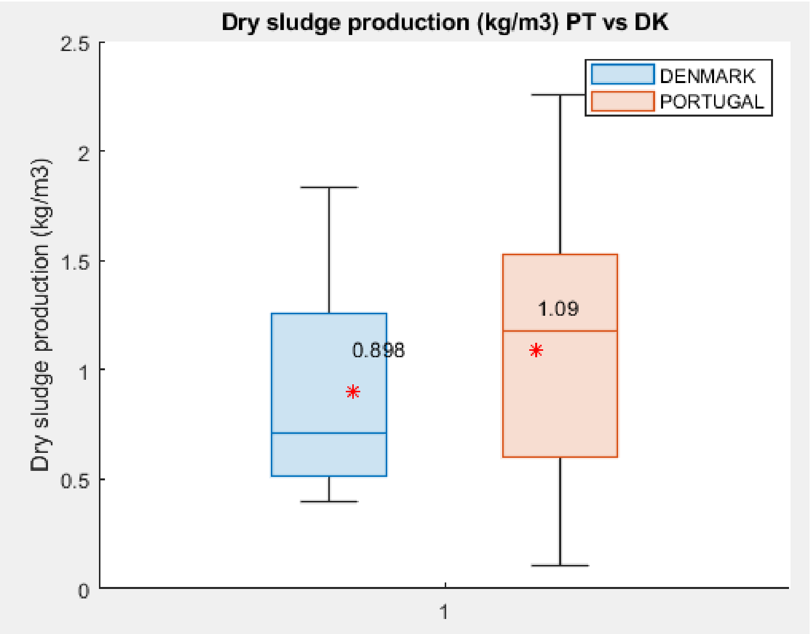


Figure 6.12: Dry sludge production (kg/m3 treated) PT VS DK

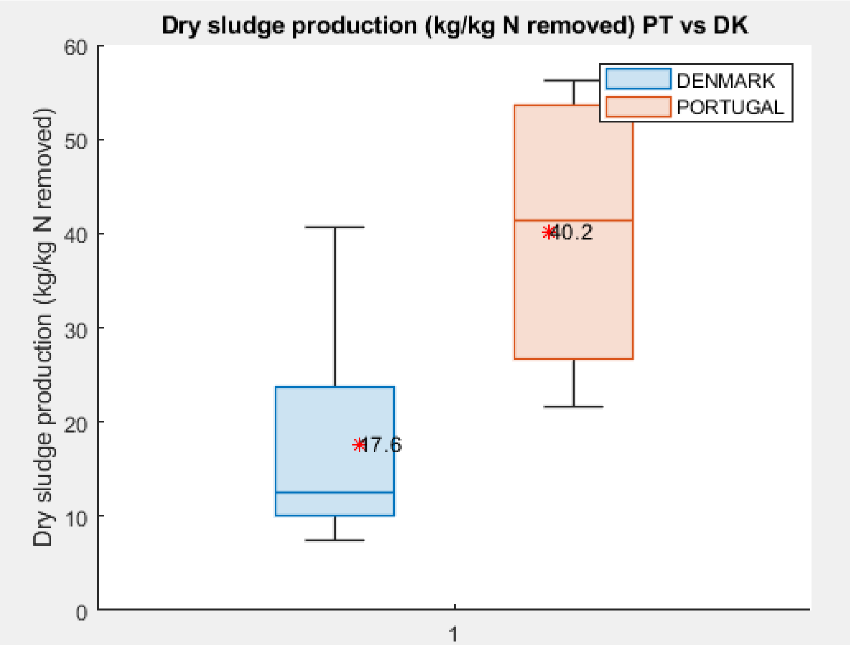


Figure 6.13: Dry sludge production (kg/kg N removed) PT VS DK

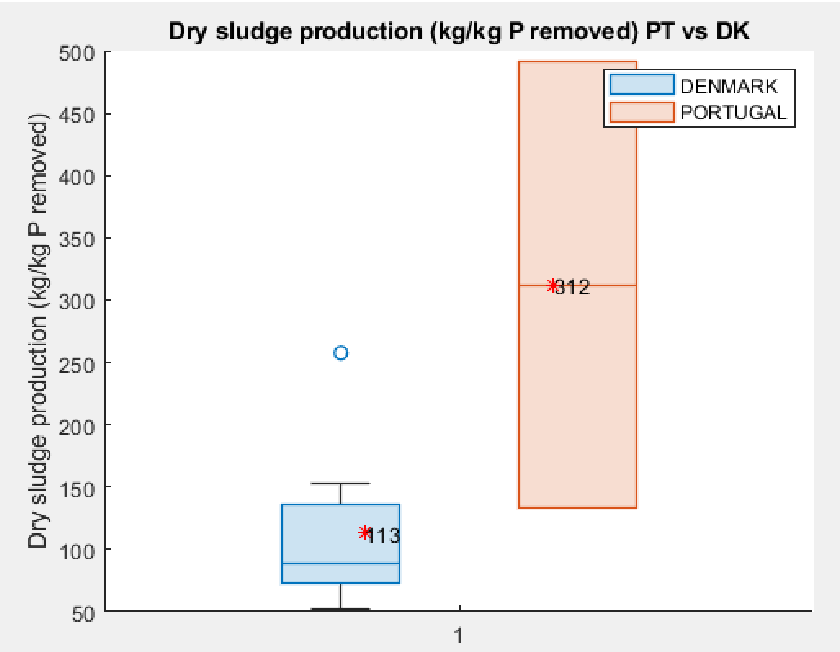


Figure 6.14: Dry sludge production (kg/kg P removed) PT VS DK

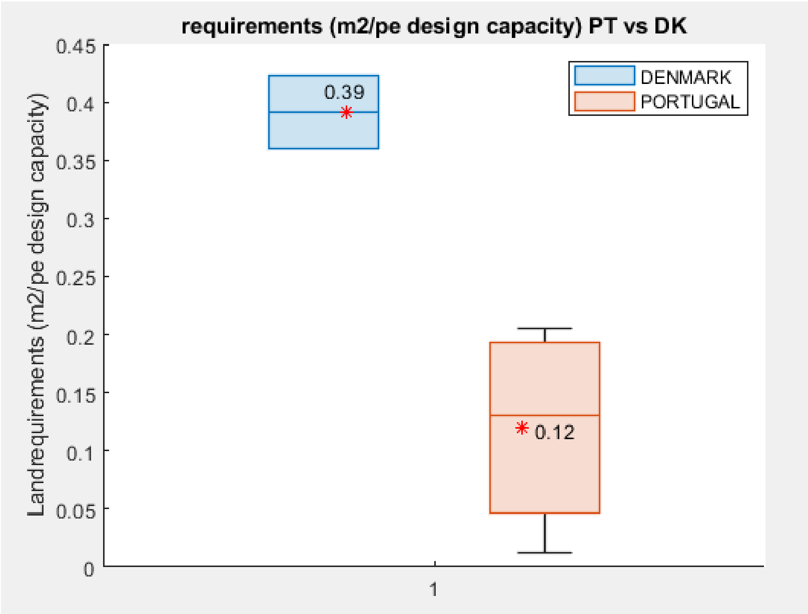


Figure 6.15: Land area requirements (m2/pe design capacity) PT vs DK

7 Applicability of Danish Nutrient Removal Strategies to Portuguese WWTPs

7.1 Chapter overview

The objective of this chapter will be describing which factors Portuguese treatment plants managing authorities will need to consider if aiming at retrofitting their plants on the example of Danish ones.

The previous chapter illustrated the main solutions Danish plants adopt to target nutrients on the water line. Now the goal will be to analyse which are the minimal requirements Portuguese plants need to possess to implement them.

The chapter will only marginally consider the economic side of these retrofits since the focus of this chapter is to say whether some retrofits are technically feasible or not. The cost of the solutions is something worth studying after having proof that the solution is technically feasible.

The choice of isolating, from the 108 Portuguese WWTPs that by law will need retrofits for nutrients removal, just the 68 adopting either a primary level treatment or having a continuous, suspended-biomass bioreactor, guides the development of this chapter.

At its core in fact there will be the study of the requirements that must be fulfilled to implement a biological nutrients removal reactor on the example of the reference Danish WWTPs. Danish WWTPs in fact, almost always tackle a substantial fraction of the nutrients load biologically, in BNR continuous, suspended biomass bioreactors. Chemical and physical processes, when present, especially in cases where very low discharge levels are required, reveal more a complementary rather than standalone function.

Multiple types of continuous suspended biomass BNR configurations exist. The most known are recalled here:

- MLE (A/O)
- BARDENPHO (A/O)
- A2/O
- (M)UCT (A2/O)
- VIP (A2/O)
- MODIFIED BARDENPHO (A2/O)

Generally, the level of detail obtained in the previous chapter concerning the bioreactor configuration was limited to state if it was an A/O or A2/O system. Unfortunately, in almost all cases it was not possible to distinguish exactly which type of configuration the reference Danish WWTPs adopted. However, the core principles remain the same and typically the configurations vary for the type of internal recycles they are equipped with. As a first level study, the key factors underlying the feasibility of implementing a system mainly based on a BNR continuous suspended biomass bioreactor were considered to depend just on the fact of having an A/O or an A2/O configuration.

The chapter will be structured as follows:

Firstly, the key factors that determine the feasibility of having a, well performing continuous, suspended-biomass bioreactor achieving biological nutrients removal will be identified. Typical ranges for these factors and possible consequences of having them out of the optimal ranges will be highlighted. The results will be presented through tables.

Secondly, each of the factors will be studied singularly. The analysis will start assuming the value taken by the factor is not in a recommended range. The analysis will then go on trying to derive possible strategies to influence the values assumable by the factor to guarantee that the requirements for a working biological nutrients removal bioreactor are fulfilled. Similarly, this second part results will be presented with tables.

The requirements will be studied singularly neglecting in a first phase the complexity induced by the interdependencies existing between these key factors.

To make things clearer, the analysis will develop suggesting strategies to adjust the situation imaging that only one of the requirements is not fulfilled at a time.

It is very likely that, if the advised strategies were implemented, they would have cascade effects on other factors, causing maybe other key requirements, initially satisfied, to become incompliant.

Being the correlations between these factors not easily predictable, one would need to study, case by case, how:

- mass balances, momentum balances, energy balances
- hydraulic patterns, mixing phenomena, mass and heat transfer phenomena
- physical space requirements and equipment requirements

would be affected when trying to implement one of the suggested strategies to address a requirement still not fulfilled, and how these latter would impact on the other requirements.

Obviously, this is not achievable through a very general level analysis like this.

However, an effort will be made to highlight from time to time when it’s highly expectable that a strategy meant to influence a specific factor will directly influence also others.

7.2 Optimal ranges for the key parameters describing a BNR system

Three key requirements dictate the feasibility of implementing BNR in a bioreactor:

- Physical properties and composition of influent feed to bioreactor
- SRT required
- MLSS

HRT is derived after the volume required for the bioreactor is computed. The required volume is principally a consequence of SRT, influent load and MLSS.

Anaerobic, anoxic and oxic HRT fractionation is a quite standardized procedure instead. Even if it’s not a primary design parameter some recommended values for the HRTs will be given.

The analysis will start with the characteristics of the bioreactor feed.

Table 7-1: Bioreactor influent temperature ranges for optimal BNR

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
Temperature	15-20 °C	At T < 15 °C nitrification is very slow	Ogunlaja, 2015
		At T > 20 °C GAO's are favoured over PAO's	Ogunlaja, 2015
	10 °C minimum temperature for nitrification and denitrification		Advanced Wastewater Treatment – Notes and Study Guides
	15 °C minimum temperature for EBPR		Advanced Wastewater Treatment – Notes and Study Guides
	25-35 °C	high temperature drops Oxygen transfer efficiency to liquid phase and microbial communities become stressed	Metcalf & Eddy, 5th ed, 2014

Table 7-2: Bioreactor influent pH ranges for optimal BNR

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
pH	7,5 - 8,5 for nitrification	pH outside optimal values may result toxic for biomass	Advanced Wastewater Treatment – Notes and Study Guides
	7 - 8 for EBPR		Advanced Wastewater Treatment – Notes and Study Guides
	7 - 7,5 for nitrification		Daigger, 1993
	pH should be kept between 6.5 and 8.5 for the flocculation process		Metcalf & Eddy, 5th ed, 2014
	5-9 for COD removal		Nitrogen Removal Fundamentals

Table 7-3: Bioreactor influent alkalinity (as $CaCO_3$) ranges for optimal BNR

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
Alkalinity	7,2 mg of $CaCO_3$ consumed per mg of Nitrate-nitrogen produced	if low alkalinity levels nitrification inhibited and pH drops risk	Daigger, 1993
	3,6 mg of $CaCO_3$ produced per mg of Nitrate-nitrogen reduced to molecular Nitrogen		Daigger, 1993
	Do not let alkalinity value drop below 40-50 mg/L of $CaCO_3$		waterandwastewater.com, 2024
	optimal alkalinity range to maintain nitrifying populations is 50-100 mg/L at the end of aeration zone		waterandwastewater.com, 2024
	(1 mg of Ammonia-nitrogen oxidized gives 1 mg of Nitrate-nitrogen, obviously 1 mg of Ammonia doesn't give 1 mg of Nitrate when oxidized)		waterandwastewater.com, 2024

Table 7-4: Bioreactor influent TSS ranges for optimal BNR

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
TSS	60-150 mg/L derived from 50-70% removal with a well-designed primary treatment on typical raw influent with TSS around 200-300 mg/L	mass transfer phenomena limited; mixing phenomena limited; excessive aeration requirements due to entrapped COD	SUSBIO
		reduction of active biomass fraction in the sludges	Metcalf & Eddy, 5th ed, 2014
			HACH

Table 7-5: Bioreactor influent rbCOD/TN ranges for optimal BNR

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
rbCOD/TN	External carbon needed for nitrogen removal with influent having BOD:N ratios < 4.0	No denitrification step for lower values	WRF, 2019
	C/N influent ratio (>6-8 minimum)		Cankaya, 2025
	2,86 mg of COD per mg of Nitrate-nitrogen reduced to molecular Nitrogen		Daigger, 1993
	5 mg of BOD in the influent per mg of Nitrate-nitrogen to reduce if you don't want extra C source dosing (accounts for not readily biodegradable BOD fraction, BOD fraction assimilated in biomass and unavailable fractions due to preliminary and primary step)		BACWA
	BOD/TKN optimal range 4-7		BACWA

Table 7-6: Bioreactor influent rbCOD/TP ranges for optimal BNR

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
rbCOD/TP	COD/TP 50:1	No anaerobic P uptake	Pistocchi et al., 2023
	14 mg of VFA-potential is required to remove 1 mg of phosphorus.		Ogunlaja, 2015
	VFA-potential values within the range of 10 to 20 mg VFA/ mg Premoved		Ogunlaja, 2015
	to achieve phosphorus removal to an effluent concentration less than 1.0mg/L, the COD: TP ratio should be 40 or more		Ogunlaja, 2015

After having seen the main parameters regarding bioreactor influent the analysis moves on with the bioreactor key design factors: SRT and MLSS.

Table 7-7: Bioreactor optimal SRT ranges

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
SRT	8-15 days required for nitrification	Nitrifiers or PAO population washout for too low SRT	waterandwastewater.com, 2024
	2-4 days required for COD removal		waterandwastewater.com, 2024
	3-5 days required for EBPR	If SRT is higher GAO start to have an advantage over PAO	waterandwastewater.com, 2024
	removal of soluble BOD: 1-2 days; removal of particulate organics: 2-5 days		Metcalf & Eddy, 5th ed, 2014
	biological phosphorous removal: 2-4 days		Metcalf & Eddy, 5th ed, 2014
	operative nitrification SRT is typically 1,5-2 times minimum nitrification SRT		Daigger, 1993
	10-25 days for UCT configuration		Ogunlaja, 2015
	5-25 days for A2/O configuration		Ogunlaja, 2015
	10-20 days for modified bardenpho configuration	aerobic SRT is largely dependent on temperature and DO setpoint	Ogunlaja, 2015
	0,5 - 1 days for COD removal 4-15 days for nitrification		BACWA

Table 7-8: Bioreactor optimal MLSS ranges

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
MLSS	2000-6000 mg/L	Too high values lead to high viscosity systems which lower oxygen transfer efficiency and mixing	FLUVYL, 2025
		Increase aeration demand and risk of dead zones	Metcalf & Eddy, 5th ed, 2014
		Too high values give sludge blanket issues in the secondary clarifier	Metcalf & Eddy, 5th ed, 2014
	3000-4000 mg/L of MLSS in UCT, A2/O and modified bardenpho configurations	too high values lead to non-optimal F/M and DO levels causing foaming and filamentous problems linked to the type of microorganisms that proliferate	Metcalf & Eddy, 5th ed, 2014 Ogunlaja, 2015
	1500-4000 mg/L		Fath, Jorgensen, 2020

To end this first part of the analysis recommended HRT values or fractions are given. These HRT are not imposed straightly but are the result of the bioreactor volume, function of SRT, MLSS, and of the influent load. The derived total HRT and its repartition in anaerobic, anoxic and oxic fractions must be crosschecked to be sure that:

- Anaerobic zone P-uptake potential is adequate
- Anoxic zone denitrification potential is adequate
- Aerobic zone nitrification and COD removal potential is adequate

In case this doesn't happen, changes in the operative MLSS and SRT or use of different zones repartition fractions must be considered. The last option is check if it's possible to build extra tanks.

Table 7-9: Bioreactor optimal aerobic HRT ranges

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
aerobic HRT	4-12 h for UCT configuration	Too high values lead to excessive aeration requirements and possible lost of denitrification and P uptake capacity	Ogunlaja, 2015
	4-6 h for A2/O configuration	Too low values lead to insufficient COD removal and nitrification, and possible filamentous microorganisms growth	Ogunlaja, 2015
	4-12 h for first step + 0,5-1 h for second step in modified bardenpho configuration		Ogunlaja, 2015

Table 7-10: Bioreactor optimal anoxic HRT ranges

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
anoxic HRT	2-4 h for post DN configurations	Anoxic HRT should be adapted to the rate at which COD is biodegraded by biomass and nitrates recycled; It could be necessary to increase COD bioavailability or nitrates recycle to compensate for a low available anoxic HRT in case it's not possible to increase anoxic zone size	WRF, 2019 Daigger, 1993
	Anoxic HRT available with a typical anoxic fraction of 0,2-0,3		SPANS
	2-4 h with UCT configuration		Ogunlaja, 2015
	0,5 - 1 h with A2/O configuration		Ogunlaja, 2015
	1-3 h first step + 2-4 h second step in modified bardenpho		Ogunlaja, 2015

Table 7-11: Bioreactor optimal anaerobic HRT ranges

Factor	Range of optimal values for BNR	Problems linked to values outside optimal range	Sources
anaerobic HRT	Typical anaerobic fraction: 0,1 - 0,2		SPANS
	0.5–0.75 h considering the maximum dry weather flow and recirculation of the sludge.		Pistocchi et al., 2023
	hydraulic residence time in the anaerobic zone is 0.75 to 1.0 hour based on the process influent flow rate.		Daigger, 1993
	1-2 h with UCT configuration		Ogunlaja, 2015
	0,5-1,5 h with A2/O configuration		Ogunlaja, 2015
	0,5-1,5 h with modified bardenpho configuration		Ogunlaja, 2015

The suggested ranges section is over. Now the work continues with possible strategies to address values that must be brought back within optimal ranges.

7.3 Strategies to modify the values of the key parameters

Table 7-12: Possible strategies to address non optimal bioreactor influent temperature

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
Temperature	if temperature is too low cover the tanks if temperature is too high allow to cool introducing equalization tank		WALCHEM
	Introduce heat exchangers in water line	Need to have auto cleaning surfaces to lower fouling	WALCHEM
	Introduce heat pumps on final effluent and then connect them to the bioreactor feed through heat exchangers		HUBER

Table 7-13: Possible strategies to address non optimal bioreactor influent pH

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
pH	introduce an equalization tank and dose there chemicals	storage of chemicals requires safety procedures and extra tanks	waterandwastewater.com, 2024
	introduce a continuous pH control system within existing tanks	frequent maintenance and calibration of pH sensors required	waterandwastewater.com, 2024
		Choose chemicals not corrosive or adapt dosing and mixing system	waterandwastewater.com, 2024
		sometimes pH adjustment strategies increase sludge production	waterandwastewater.com, 2024
		some chemicals used for pH adjustment release secondary pollutants	waterandwastewater.com, 2024

Table 7-14: Possible strategies to address non optimal bioreactor influent alkalinity

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
Alkalinity	Dose alkalinity source; a storage, dosing, mixing, control system is required	Corrosion-resistance materials may be required	waterandwastewater.com, 2024
		sludge production might rise	waterandwastewater.com, 2024
		scaling can happen	waterandwastewater.com, 2024

Table 7-15: Possible strategies to address non optimal bioreactor influent TSS

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
TSS	Introduce grit removal or primary sedimentation if missing	reduction of available C for BNR with new primary sedimentation	
	Introduce pre-filtration step if necessary	Reduction of available C for BNR unless filtrate stream is sent to solid-liquid subsequent separation unit	Blue Water; Salsnes Filter, (2024)
	Introduce CEPT	Phosphate can be precipitated	WRF, 2022

Table 7-16: Possible strategies to address non optimal bioreactor influent rbCOD/TN

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
rbCOD/TN	Dose extra C carbon source	Increased MLSS in bioreactor and increased SLR and SOR on secondary sedimentation tank; sludge blanket issues possible	WRF, 2022
		Increase in WAS	WRF, 2022
	Ferment primary sludge and recycle surnatant to anaerobic and anoxic sections of bioreactor	risk of over/under VFA production	WRF, 2022
	Ferment RAS and recycle surnatant to anaerobic and anoxic sections of bioreactor	risk of over/under VFA production	WRF, 2022
	Treat sidestreams returns from sludge line with deammonification unit if rbCOD/TN is low		NEW PORT
	Ferment primary sludge and recycle surnatant to anaerobic and anoxic sections of bioreactor	reduced biogas production	HACH

Table 7-17: Possible strategies to address non optimal bioreactor influent rbCOD/TP

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
rbCOD/TP	Dose extra C carbon source	Increased MLSS in bioreactor and increased SLR and SOR on secondary sedimentation tank; sludge blanket issues possible Increase in WAS	WRF, 2022
	Ferment primary sludge and recycle surnatant to anaerobic and anoxic sections of bioreactor	the fermentation process of primary sludge increases the required anaerobic HRT of extra 1-2 hours; risk of over/under VFA production; reduced biogas production	Daigger, 1993; HACH
	Ferment RAS and recycle surnatant to anaerobic and anoxic sections of bioreactor	the fermentation of RAS requires 2-3 days	Daigger, 1993;
	Avoid too long anaerobic periods in sludge line with rbCOD available otherwise P release happens and then after sludge dewatering process P rich return stream overloads water line		Ogunlaja, 2015
	Recycle RAS to anoxic and not to anaerobic zone to avoid having denitrifiers consuming rbCOD instead of PAOs		
	Dose P precipitants in return sludge dewatering reject stream	Molar ratio Fe/P or Al/P around 5-7 to achieve TP lower than 0,1 mg/L in effluent;	NEO water treatment
	Dose precipitants in main water line	Some chemicals consume alkalinity bonding with hydroxide ions rather than with phosphates. Extra precipitants dosages and chemicals to post adjust pH required; 0,92 mg of CaCO3 consumed dosing 1 mg of FeCl3 and 0,45 mg of CaCO3 consumed dosing 1 mg Al2(SO4)3	WRF, 2022; NEO water treatment

Table 7-18: Possible strategies to manipulate SRT

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
SRT	act on WAS rate	Increased MLSS in bioreactor and increased SLR and SOR on secondary sedimentation tank; sludge blanket issues possible	waterandwastewater.com, 2024
	act on Temperature to influence biomass growth and decay rate	Probable difficulties in induce the required temperature change to truly influence SRT target	Metcalf & Eddy, 5th ed, 2014
	Manipulate DO set point during aerobic phase to influence biomass growth and decay rate	Possible difficulties in preserving anoxic and anaerobic zones and increased aeration costs	
	change anaerobic/anoxic/oxic volume repartition to influence biomass growth yield		
	change the point from where you waste to manipulate TSS in the waste stream		Metcalf & Eddy, 5th ed, 2014

Table 7-19: Possible strategies to manipulate MLSS

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
MLSS	manipulate influent organic load through primary treatment	rbCOD/tN and rbCOD/TP may be affected	FLUVYL, 2025
	act on WAS and keep track of F/M and SVI to notice the effects	change in sludge production and SRT possible	FLUVYL, 2025
	Manipulate DO set point during aerobic phase to influence F/M and the type of dominating microorganisms	Possible difficulties in preserving anoxic and anaerobic zones	FLUVYL, 2025
	Avoid spikes in influent load adding an equalization tank to give longer HRT in bioreactor and avoid biomass washout		FLUVYL, 2025

Table 7-20: Possible strategies to manipulate aerobic HRT

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
aerobic HRT	introduce intermittent aeration with lower DO target in aerobic zones if the aerobic HRT must be lowered	need to change aeration system and aeration control system	
	Change aeration system to improve oxygen transfer efficiency	calibrated and well maintained DO sensors required	waterandwastewater.com, 2024
	add equalization tank to lower peak/average influent ratio and lower the impact of shock loads		
	Introduce UASB step pre bioreactor to increase bioavailability of substrate		INOVAR
	Introduce advanced oxidation unit pre bioreactor to increase rbCOD and decrease recalcitrant COD and toxic substances		INOVAR
	adopt step feeding to lower aeration needs or to increase MLSS which should lower aerobic HRT required		WRF, 2022

Table 7-21: Possible strategies to manipulate anoxic HRT

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
anoxic HRT	Variable size of aerobic-anoxic zones determination through activation/deactivation of finely tuned aeration system	Capacity to achieve a fine control of the aeration system required	ENVIROMIX
	Add extra partitioning to assure to have adequate anoxic HRT	Head losses in the tank due to partitioning might surpass admissible value; mixing problems may rise	
	In aerobic zone work with very low DO levels to achieve stratification in flocs (same principle of granular sludge) and have simultaneous nitrification/denitrification in the same floc	You need a granular biomass selection unit that recycles only well settling biomass	BACWA
	manipulation of nitrates internal recycle to influence nitrates load	Extra pumping and piping capacity may be required	
		Need of a control strategy to adapt the internal recycle stream with changing conditions	Daigger, 1993
		(Nitrates recycle pumping capacity is typically 200-400% of raw influent)	Daigger, 1993
	manipulation of denitrifying biomass concentration in bioreactor through SRT and nitrates recycle	Bioflocs and inert solids are recycled together with nitrates increasing TSS but not forcely VSS in bioreactor	
	Dose extra C carbon source to increase fraction of rbCOD that is faster to use for denitrifying biomass		Metcalf & Eddy, 5th ed, 2014

Table 7-22: Possible strategies to manipulate anaerobic HRT

Factor	strategy to address values out of specified range for optimal BNR	Side effects of the suggested strategy	Sources
anaerobic HRT	introducing baffles and partitioning in bioreactor tank	Added partitioning compatible with head losses and mixing requirements in the tank; is there risk of overflooding or short-circuiting or dead zones presence?	
	introduce anaerobic selector tank		SULZER; ENVIROMIX
	use part of primary sedimentation tank as anaerobic selector		
	Chemical P removal to complement insufficient biological removal	Precipitants storage tanks and dosing system required. Control strategy for precipitants dosing needed; Ensure that the receiving pipe or tank is compatible with the chemicals used.	WRF, 2022
	Dose 2 - 10 mol precipitant /mol P to remove to have effluent P between 0,7 and 0,1 mg/L using Fe based precipitant	Some chemicals consume alkalinity: Alkalinity consumption between 0,51 and 0,92 mg CaCO3 per mg of precipitant (Sodium aluminate is an exception, it increases alkalinity)	WRF, 2022
	Dose 2 - 6 mol precipitant /mol P to remove to have effluent P between 0,6 and 0,1 mg/L using Al based precipitant		
		WAS increase and complex future recovery of P; extra chemical sludge production between 0,26 and 1,5 mg TSS per mg of precipitant used	WRF, 2022
		Unwanted precipitation of needed rbCOD unless post precipitation is adopted In case of post precipitation additional tanks required mixing required in precipitation zone, but mustn't be excessive to avoid air entrainment	

7.4 Expected Initial Performance Improvements from Danish-Inspired Retrofit of Portuguese WWTPs

To estimate a first order of magnitude in performance change due to the implementation of a Danish inspired model in the Portuguese context, Spain was used as reference. Spain in fact, could be seen as an intermediate step for the evolution of Portugal towards Denmark (Table 7-23). Spanish WWTPs performances are used as a reference for the possible performances of Portuguese WWTPs gradually modifying their treatment lines based on the Danish model.

Table 7-23: Comparison of starting situations for Portugal, Spain and Denmark (WISE, 2025)

WISE,2025	PORTUGAL	SPAIN	DENMARK
WWTPs with primary level of treatment	8	33	0
WWTPs with secondary level of treatment	394	750	14
WWTPs with nutrients removal level of treatment	90	1046	316
% of national design load treated in primary level WWTPs	8,5	1,3	1,7
% of national design load treated in secondary level WWTPs	78,5	68,0	8,3
% of national design load treated in nutrients removal level WWTPs	13,1	30,7	90,0
% of national design load still to collect	0,0	0,4	0
% of national design load still to submit to secondary level of treatment	6,0	4,6	0,1
% of national design load still to submit to nutrients removal level of treatment	2,8	4,2	0,3
% of the load to submit to secondary level of treatment missing secondary level of treatment	9,7	9	0,1
% of the load to submit to nutrients removal level of treatment missing nutrients removal level of treatment	21,5	13,8	0,3

As Table 7.23 shows, Spain seems to have achieved a more advanced level nationally compared to Portugal with respect to nutrients removal.

It must be said that Spain seems to classify a substantial fraction of its territory as eutrophication sensitive. This may be the reason behind the higher proportion of national load submitted to nutrients removal compared to Portugal (Figure 7.1).

Values reported for Spanish WWTPs can be used to give the reader the idea of an intermediate situation between the Portuguese and the Danish one. It is very likely that, in the process of transitioning towards the Danish model, Portugal will step through the present Spanish situation in the attempt of improving its nutrients removal performances.

One big limit of this approach is that there is no clear data on the most spread type of process used to target nutrients removal in the Spanish context. The assumption here made it’s that it consists of a biological process, on the Danish example. Obviously, this assumption should be checked to be able to actually use Spanish data as a reference for a near future situation for the Portuguese wastewater treatment sector.

That said, Spanish WWTPs performances are therefore presented in Table 7-24 and Table 7-25. Comparing Spanish and Portuguese performances these are the first results:

- lower Spanish energy demand from the grid
- probable lower sludge production for the Spanish context after the dewatering (data for Portuguese WWTPs were on a dry basis while Spanish ones are on a wet basis)
- lower Spanish effluent composition in terms of N and P discharged

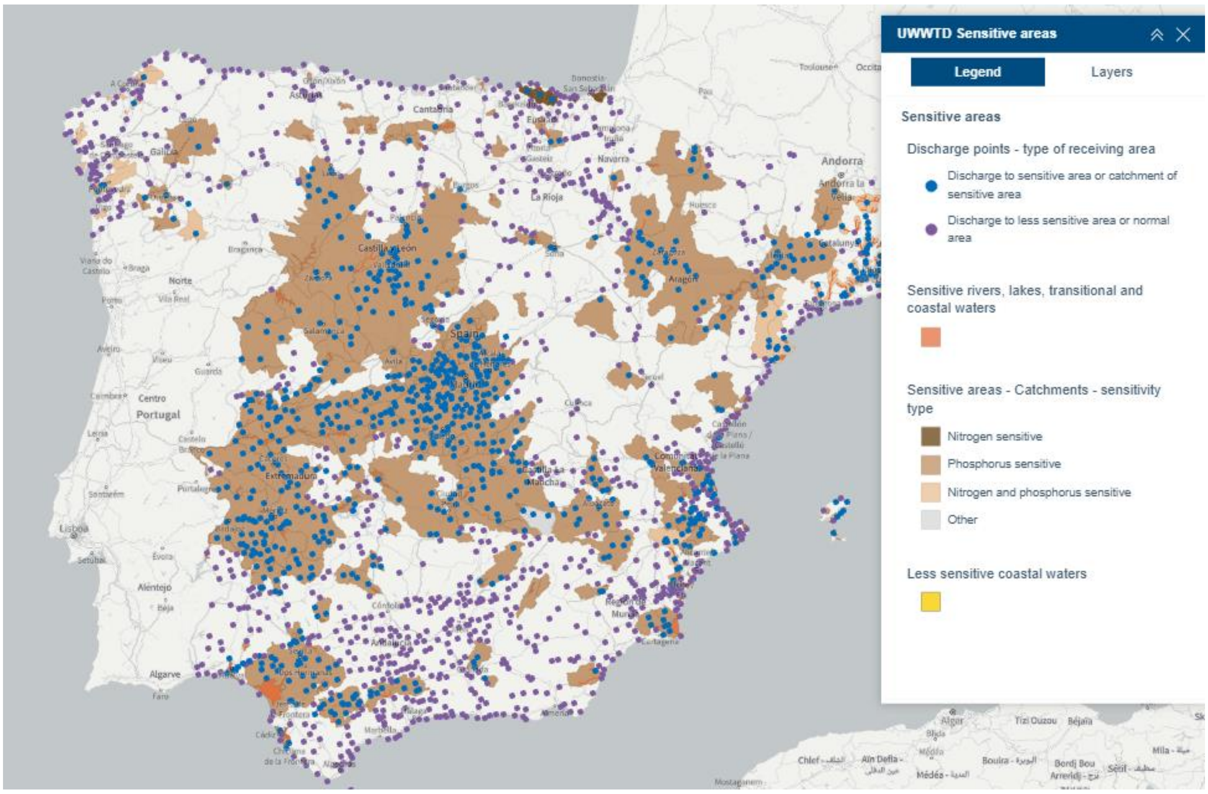


Figure 7.1: Spain map of nutrients-sensitive zones (WISE, 2025)

Table 7-24: LCA of 22 Spanish WWTPs (Toja et al., 2016)

	Spanish AVG
TN effluent (mg/L)	17,44
TP effluent (mg/L)	2,25
COD effluent (mg/L)	83,29
TN % removal	57,13
TP % removal	64,23
COD % removal	83,06
Chemicals consumption (kg/m3)	0,0115
electricity consumption from the grid (kWh/m3)	0,36
Sludge production (kg/m3)	0,68
Biogas Generation (kWh/m3 treated)	

Table 7-25: LCA of 24 Spanish WWTPs (Garcia et al., 2011)

SPAIN AVERAGES	secondary level WWTPs	nutrients removal level WWTPs discharging in non-sensitive areas	nutrients removal level WWTPs discharging in sensitive areas	WWTPs designed for treated water reuse (mainly internal or for irrigation)
TN effluent (mg/L)	15,0	17,4	10,3	26,5
TP effluent (mg/L)	1,4	1,5	0,7	1,87
COD effluent (mg/L)	35	39,0	24	45
TN % removal	54	69,5	80	55,9
TP % removal	60,4	83,5	90	76,3
COD % removal	92	94,7	96	94,3
Chemicals consumption (kg/m3)	0,022	0,022	0,048	0,074
electricity consumption from the grid (kWh/m3)	0,27	0,50	0,47	0,66
wet Sludge production (kg/m3)	0,56	1,1	1,2	1,35
Biogas Generation (kWh/m3 treated)	0,17	0,05		0,16

Data on biogas production have a low trustability deriving from a sample of very limited size.

Not having data on chemicals usage for the Portuguese WWTPs and not having those on land demand for the Spanish no other comparison is possible.

7.5 Economic Order of Magnitude of the investments required to retrofit WWTPs inspired by the Danish model

Portuguese WWTPs managing authorities will soon need to start considering which options are available to adapt to the updated standards in terms of nutrients removal.

In section 6.4, biological nutrients removal thanks to an alternation of anaerobic, anoxic and oxic sections (A2O), possibly through an internal repartition of the available aerated bioreactor volume, has been proposed as a valid way of retrofitting conventional continuous activated sludge systems (CAS).

As already repeated several times, the positive effect of this model depends on subsidiary strategies.

Having an infrastructure that enables, among others:

- dosing an external C source or ferment influent
- completion of P removal with chemicals precipitants
- smart control of aeration patterns with changing inflow conditions
- stormwater diversion and retention
- internal and external mixed liquors recycle online control
- sludge line reject water separate treatment before recycle into main water line

is of key importance to see a successful implementation.

It has already been stated that some existing WWTPs may not possess the physical space requirements to host this infrastructure. However, under the hypothesis that the space requirements are fulfilled, it would be interesting to have some order of magnitude estimation of the required investments to retrofit a CAS to an A2O or A/O coupled with chemical P removal.

To do so a web review of completed retrofits has been performed. Not many publicly available results have been found. Despite that a very rough first estimation has been derived from those studies. It must be noted that usually retrofits involved multiple interventions, not only related to enhance nutrients removal performance. Due to the difficulty in isolating the financial burden related to increasing nutrients removal, the overall budget and the main interventions performed during the retrofits will be mentioned. Moreover, most of the times the change in terms of nutrients removal after WWTPs upgrading was not declared publicly. All these factors should be considered during the subsequent analysis of the costs reported.

A trustable estimation of the investments required to adapt a CAS to the nutrients removal standards, apart from counting just the investment required for the nutrients removal units, would show the change in nutrients removal performances due to the upgrading to see if the efforts paid off.

All these factors confirm that the values that will be presented in the following tables must be only seen as first rough order of magnitude guesses.

When civil works where performed for buildings, tanks and pipings, the capital costs were divided for an expected life of 40 years, whereas, where civil works involved aeration, mixing, pumping, and control equipment, 10 years lifetime was chosen. (*EPA*, 2003)

These choices are obviously very approximative but being the estimation already quite rough it made little sense to be accurate just in determining equipment life span. CAPEX divided by equipment life expectancy summed to OPEX (when available), where divided by volume treated per year to give an estimate of the retrofit investments required in terms of euros/m3 treated.

Three types of situations will be presented:

- Investments to retrofit CAS WWTPs on Danish example:
- Investments to enhance nutrients removal performances acting on infrastructure different from the bioreactor:
- Investments to enhance nutrients removal (and general performances) of WWTPs that already implement nutrients removal:

For each situation, one or more case studies will be briefly illustrated.

The first situation is the hypothetical scenario for a Portuguese WWTP fulfilling the requirements to implement an A2/O or an A/O system coupled with chemical P removal. Exactly the core of the Danish model.

The second situation applies to all those WWTPs that do not possess the requirements to retrofit the core of their biological process to target nutrients. Still, following the example of Danish WWTPs, there are many auxiliary infrastructures that play a vital role in determining the whole WWTP efficiency, Upgrading those auxiliary infrastructures could be feasible and give tangible results too.

The third situation refers to a hypothetic future scenario for retrofitted Portuguese WWTPs, and a reality for Danish ones. WWTPs already satisfying the new standards for nutrients removal will need retrofits to improve the efficiency of their processes in terms of resources consumption and recoverability.

7.5.1 Investments to retrofit CAS WWTPs on Danish example:

(*Lantania*, no date) reports to have retrofitted CAS Vale do Vinalopo WWTP engaging to build: new intake equipment, new distribution chamber, change in aeration and pumping system, abatement of primary sedimentation, introduction of anoxic volume and quaternary treatment. Unfortunately no information on land requirements for the upgrade was found. Due to the different nature of the retrofit intervention half of the CAPEX have been considered to have an amortization period of 40 years, and half of 10 years.

Table 7-26: Vale do Vinalopo, retrofit

WWTP	Vale de Vinalopo, Spain
SIZE (PE)	110000
VOLUME CAPACITY (m3/d)	24000
VOLUME TREATED (m3/d)	12000
INITIAL CONFIGURATION	CAS
CAPEX (euros)	9600000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	21
RETROFIT YEAR START	2023
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,14

An Indian CAS WWTP was retrofitted without any land requirement improving considerably N removal. These were the changes brought by the retrofit interventions: Introduction of anoxic zone in aeration tank by switching off some surface aerators, optimization of HRT and DO in the aerobic-anoxic sections without modifications of recycle ratio and MLSS through diffuse aerators replacements and DO sensors addition (Mohan et al., 2022).

Due to the nature of the interventions a 10 years depreciation period was chosen for the CAPEX.

Table 7-27: K&C CAS WWTP retrofit (Mohan et al., 2022)

WWTP	K&C, India

SIZE (PE)	
VOLUME CAPACITY (m3/d)	
VOLUME TREATED (m3/d)	55000
INITIAL CONFIGURATION	CAS
CAPEX (euros)	338360
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	8
RETROFIT YEAR START	2021
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,0017

The type of intervention, involving minimal infrastructure modifications, allowed to have little costs.

El prat de Lobregat WWTP was retrofitted in 2006 to achieve biological nutrients removal with the introduction of anoxic and anaerobic sections in the bioreactors. The investment to do so was considered again to be partitioned equally in 10 and 40 years depreciation time not knowing any detail for the retrofit (*Water Reuse Barcelona*, 2011). Unfortunately no information on land requirements for the upgrade was found.

From EU dataset the volume treated was reported to be half of the design capacity one.

Table 7-28: El prat de Lobregat CAS WWTP retrofit

WWTP	El prat de Lobregat, Spain
SIZE (PE)	2275000
VOLUME CAPACITY (m3/d)	420000
VOLUME TREATED (m3/d)	200000
INITIAL CONFIGURATION	CAS
CAPEX (euros)	15600000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	
RETROFIT YEAR START	2006
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,013

The lower specific costs compared to Vale do Vinalopo case can be attributed to an higher WWTP size.

Guadarrama medio CAS WWTP (*Canal de Isabel II*, 2017) has been retrofitted to expand treatment capacity (almost doubling it) and enhance N & P removal P and quaternary treatment for wastewater reuse (*Comunidad de Madrid*, 2024). Again, not having details on the retrofit strategies the same considerations on depreciation time of CAPEX are always used if not differently specified. Unfortunately no information on land requirements for the upgrade was found.

Table 7-29: Guadarrama medio CAS WWTP retrofit

WWTP	Guadarrama medio, Spain
NEW SIZE (PE)	140000
OLD VOLUME CAPACITY (m3/d)	17500
NEW VOLUME CAPACITY (m3/d)	30000
INITIAL CONFIGURATION	CAS
CAPEX (euros)	17077263
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	
RETROFIT YEAR START	2024
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,097

Denmark model showed that the most plausible ways to retrofit a CAS are, either an A2/O system or an A/O one coupled with chemical P removal. Since now the chapter has evolved around the first case. Vienna WWTP is a good reference for the second.

Vienna CAS WWTP was enlarged and retrofitted between 2000 and 2005 through the installation of a second biological treatment stage for biologically eliminating nitrogen and chemically eliminating phosphorous, following the first biological stage for organic matter removal and nitrification dating back to 1980 and connected to a secondary sedimentation step. Sludge line extension was part of the retrofitting too (*WTE*, no date) (*WKU*, no date).

Table 7-30: Vienna WWTP retrofit

WWTP	Vienna, Austria
SIZE (PE)	3200000
NEW SIZE (PE)	4000000
NEW VOLUME CAPACITY (m3/d)	680000
INITIAL CONFIGURATION	CAS + chem P precipitation
CAPEX (euros)	225000000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	60
RETROFIT YEAR START	2000
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,057

The lower specific investments can be attributed both to an high WWTP size, to the older period of the upgrade and to the choice of using chemical rather biological P removal.

7.5.2 Investments to enhance nutrients removal performances acting on infrastructure different from the bioreactor:

Here some alternative approaches are mentioned, mainly meant to overcome space limitations when trying to improve nutrients removal performances of existing WWTPs. The focus so will shift from bioreactor retrofit to move to general WWTP retrofit.

Until now it has been considered that to improve nutrients removal one can act mainly on the bioreactor. However, Tallin WWTP claims to show that this improvement can be achieved even retrofitting secondary sedimentation tanks with lower investments in terms of space and infrastructure. The reconstruction of the secondary sedimentation tanks will come with the renewal of its sensors and control system. (*Tallina Vesi*, no date)

Table 7-31: Tallin WWTP secondary sedimentation retrofit

WWTP	Tallin, Estonia
SIZE (PE)	500000
VOLUME CAPACITY (m3/d)	130000
USED VOLUME CAPACITY (m3/d)	
CONFIGURATION	BIOFILTRATION
CAPEX (euros)	9000000
OPEX (euros/year)	
TIME REQUIRED FOR THE CONSTRUCTION (months)	30
CONSTRUCTION YEAR START	2024
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,012

Gotha WWTP was originally built with an anoxic-oxic bioreactor followed by a tank where chemical P precipitation happened. However, its retrofit, based on modernization of control, mixing and aeration system in the bioreactor, it's a good example of what has already been stated. Improving the existing bioreactor performance maintaining its infrastructure can lead to a cost-effective solution (*Passavant-Geiger*, no date). EU data were used to fill the gap for volume treated and used capacity. A 10 years depreciation time was considered for this retrofit.

Table 7-32: Gotha WWTP retrofit

WWTP	Gotha, Germany
SIZE (PE)	150000
USED CAPACITY (PE)	69816
USED VOLUME CAPACITY (m3/d)	13740
CONFIGURATION	A/O + chem P precipitation
CAPEX (euros)	420000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	12
RETROFIT YEAR START	2013
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,008

Expanding an existing infrastructure by building a second level above the tanks could represent a possibility. Bleesbréck WWTP proved it (*Bruck-Weckerle*, no date).

As Denmark example showed, investments in the sewer network are essential to achieve the best performances possible for WWTPs. Tallin will try to improve its wastewater management and stormwater collection infrastructure. Through a renovation program 45 km of collectors will be substituted, a CHP unit will be built and an automated control system of the WWTP will be put in place. Overall a 40 million euros commitment for a 2 years period. (*NIB*, 2023)

7.5.3 Investments to enhance nutrients removal (and general performances) of WWTPs that already implement nutrients removal:

It would be interesting now to see what a first guess of the investments required to upgrade WWTPs already possessing a biological nutrients removal section (A2/O). These could be helpful for future retrofitting of Portuguese WWTPs which may struggle to adequate all in once to all the new standards and may pass through multiple steps of retrofitting. Graz WWTP is a good example.

Already having biological nutrients removal, its expansion and retrofit is planned now to furtherly improve nutrients removal, match the needs of quaternary treatment, growing population and stormwater overflows.

Its upgrade is based on: construction of an additional aeration basin, renewal of pumps, machines and aggregates, addition of quaternary treatment, separate management of rain waters, improvements to sludge line and extensive online process control introduction (*Holding Graz*, no date)

Table 7-33: Graz WWTP retrofit

WWTP	Graz, Austria
SIZE (PE)	500000
NEW SIZE (PE)	815000
NEW VOLUME CAPACITY (m3/d)	140000
INITIAL CONFIGURATION	A2/O
CAPEX (euros)	83000000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	42
RETROFIT YEAR START	2025
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,10

Upgrading WWTPs already designed to achieve nutrients removal seems more expensive than upgrading WWTPs yet not ready for biological nutrients removal. A possible explanation is that to achieve very high performances the technologies required must differ from the biological ones, namely the cheapest.

In this chapter the factors regulating the possibility of having a continuous suspended biomass bioreactor that achieves BNR have been discussed. It's easy to foresee that not all Portuguese WWTPs will find a way to satisfy all the requirements needed to follow the Danish example. For this reason, a separated chapter will be devoted to complementary/alternative solutions to continuous, suspended biomass bioreactors. Retrofit investments to upgrade existing WWTPs not possessing the requirements to implement a biological nutrients removal step in their existing structure will be quickly discussed too, either considering alternative technologies or the entire rebuilding of the WWTP from scratch.

8 Alternative/complementary solutions to continuous suspended biomass bioreactors to achieve BNR

8.1 Chapter Overview

The goal of this chapter is to explore the industrially available alternatives to continuous suspended biomass systems.

These typically include batch system, notably SBRs and AGS systems, typically implemented in SBRs.

Fixed biomass systems, such as BAFs, MBBRs and trickling filters, and hybrid fixed-suspended biomass systems, as IFAS and hybrid MBBR.

Membrane systems as MBRs and MABRs or hybrid MABRs

The aim is to provide the reader valid alternatives or complementary solutions to retrofit WWTPs that, either are not based on continuous, suspended biomass bioreactors, or will hardly ever be able to comply with all the requirements to install a BNR process in it and rely completely on it to achieve nutrients removal.

The chapter structure will be as follows: for each technology the foundational principles will be quickly illustrated. Then tables highlighting key technology characteristics will be presented and finally true retrofit or greenfield case studies results will be given when available.

Lastly a section devoted to the investments required to implement these technologies will be presented together with a comparison with the investments required to build a new WWTP rather than upgrading an existing one.

8.2 Batch and Granular Systems (SBR, AGS)

8.2.1 SBR

Sequencing Batch Reactors operate in a cyclic mode. Filling, reaction, settling, withdraw and decant phases iterate. In a unique tank the repetition of these subsequent phases allows to treat the influent. The key actor stays the suspended biomass as in the continuous flow suspended growth bioreactors. The key steps that characterize a continuous flow bioreactor stay relevant for the SBRs. Simply, instead of happening with a spatial separation, they happen with a temporal separation. Duration and features of the single phases can be adapted to target different pollutants and achieve different effluent quality. Some phases may overlap partially. By manipulating the feeding and reaction phases aeration regime, anaerobic, and anoxic intervals appear and nutrients removal is possible. SND and PN-ANAMMOX processes can happen together with EBPR. As in continuous flow regime bioreactors, also SBRs are equipable with carriers, either fixed or mobile, to have hybrid attached-suspended biomass configurations. (Dutta, Sarkar, 2015)

Interesting examples of SBRs based processes, achieving BNR, industrially available can be checked online (*Schreiber CSR*, *Parkson*, 2022)

Table 8-1: SBR technology highlights (Dutta, Sarkar, 2015)

PROCESS	SBR (Dutta, Sarkar, 2015)
KEY FEATURES	can be used under steady or unsteady state conditions; nature of the processes involved is highly nonlinear duration of Fill and React phases can be adjusted to impart the SBR system a CSTR-like or ideal PFR-like treatment characteristics Settle phase is not disturbed by the continuous inflow of new raw influent leading to typically better effluents in terms of suspended solids; no requirement of a separate clarifier unit save more than 60 % of the operating expenses required for a conventional ASP Better control, smaller foot-print area and lower investment cost needed compared to continuous flow;
REQUIREMENTS TO ACHIEVE BNR	Simultaneous nitrification/denitrification possible if C/N is around 11 C/P around 40 to have EBPR; Nitrite levels below 2 mg/L advisable, pH between 7,2 and 8
TYPICAL APPLICATIONS	In densely populated countries it is preferred due to low requirement of area as well as manpower for operation biological treatment of industrial wastewater containing difficult-to-treat organic chemicals

8.2.2 SBR-AGS

Aerobic Granular Sludge technology relies on the organization of the suspended biomass in granules rather than in flocs as usually happens in CAS. Granules are denser and bigger compared to flocs leading to a much faster settling behaviour. The granules show a layered structure where different redox conditions are kept in each layer. This conformation allows to achieve in a unique tank organic matter and nutrients removal. The factors that impact the transition from a floc-based organization of the suspended biomass to the granular one will be highlighted in Table 8-2 however one key aspect is to guarantee in the bioreactor conditions that selectively washout slowly settling biomass.

Typically, a continuous, plug flow or completely mixed hydraulic regime is not best suited to match this requirement needed to promote the granulation. This is why the process is usually implemented in batch systems such as SBRs. SBRs are best suited to promote the establishment of AGS since plug flow reactors and CSTR reactors typically have recycles that disrupt the granules formed, and secondary sedimentation tanks with long settling time that do not impose selective pressure on low velocity settling flocs which settle, and then through recycles are brought back to the reactor. Another reason behind the preferable AGS retrofit of SBRs is the cyclic nature of SBR. The aerated phase normally lasts longer than the time required to consume most of the BOD. During the final part of the aeration phase the biomass starves having already consumed most of the BOD and this leads to changes in the negative surface charge of biomass cells (due to increased hydrophobicity) favouring the flocs adhesion to granules. (Li et al. 2014)

Table 8-2: AGS technology key highlights

PROCESS	AGS	SOURCES
KEY FEATURES	Flocculent sludge agglomerates into a densely compact self-immobilized granular sludge; aerobic granules have a mean diameter greater than 200 μm; Stable granule with distinct redox micro-environments capable of simultaneously removing organics, N, and P.	(Hamza et al., 2021)
	Within aerobic granules, significantly larger amounts of extracellular polymeric substances (EPS) are produced compared to CAS leading to the formation of a hydrogel matrix that contributes to the strength and stability of granules.	(Hamza et al., 2021)
	The high concentration of biomass and the latent available and diverse micro-biological population make the process less sensitive and quicker to recover from severe process upsets.	(Geisen, 2013)
	High OLR allows for fast granulation while delayed granular formation occurs at low OLR. Low OLR 1.05–1.68 kg COD/m3day; high OLR up to 15 kg COD/m3·day	(Hamza et al., 2021)
	Seeded with normal activated sludge, full granulation of the biomass was obtained within 3 months; by seeding with granular biomass, duration of start-up can be significantly reduced	(Geisen, 2013)
	Additives Metal Cations Ca2+, Mg2+, Fe2+/Fe3+promote granulation by neutralizing common negatively charged sludge particles and enhancing adsorption/ bridging interactions	(Hamza et al., 2021)
REQUIREMENTS TO ACHIEVE BNR	if (Vs)min is less than 4 m/h, aerobic granulation is not favoured in SBR, instead the growth of suspended sludge is greatly encouraged. (typical settling velocity of conventional activated sludge is generally less than 5 m/h)	(Wang et al., 2006)
	SBR operated with a volume exchange ratio of 50-70%.	(Li et al., 2014)
	feast-famine periods during operation, short settling time, and high aeration intensity to have enough hydrodynamic shear forces, favour aerobic granulation.	(Hamza et al., 2021)
TYPICAL APPLICATIONS	Industrial effluents treatment: wastewaters rich in recalcitrant and bio refractory compounds	(Hamza et al., 2021)
TYPICAL SIDE APPLICATIONS	Waste aerobic granules are applicable for biosorption of heavy metals regardless of the physiological state of the granules - active, inactive, intact, disintegrated, compact or loose	(Hamza et al., 2021)
	Aerobic granules contain approximately 20–30% of ALE, which is twice the amounts found in CAS; ALE extraction might aid in sludge management	(Hamza et al., 2021)

Now that the key features of the technology have been shown, some case studies will be presented highlighting the feasibility of implementing AGS technology as a retrofit.

The first case is Garmerwolde one, where the WWTP, in 2014 was expanded by building a parallel treatment line based on AGS. From Table 8-4 it is apparent that nutrients removal is already quite satisfactory with P levels needing a very little adjustment to fulfil the new 2025 standards.

The second case is Osterrod WWTP, where a line of treatment was retrofitted to AGS technology while the other was left to the standard CAS layout. A comparison of the performances of the two lines is visible in Table 8-5. It must be said that the WWTP CAS line was already high performing, the similar removal achievements of the AGS line must be praised in terms of lower energy chemicals and footprint demand though.

Table 8-3: Garmerwolde pre vs post upgrade (upgrade through expansion) (Pronk et al., 2015)

INITIAL TREATMENT LINE	CHANGES DUE TO UPGRADING
capacity (pe): 186 300	capacity (pe): 315 000
screens (6mm spacing)	
grit removal tanks	
primary clarification	Addition of Influent buffer tank for parallel secondary treatment line
two stage activated sludge A-B process	AGS reactors added as a parallel secondary treatment line
secondary clarification	
Sharon reactor to treat side streams from sludge digesters and thickeners	
mixed sludge tank	excess sludge buffer tank added
mechanical sludge dewatering unit	
digester	

Table 8-4: Garmerwolde performances post upgrade (Pronk et al., 2015)

Garmerwolde	POST UPGRADE
Capacity (pe)	315 000
Effluent TSS (mg/L)	20
Effluent COD (mg/L)	64
Effluent BOD (mg/L)	9,7
Effluent TN (mg/L)	6,9
Effluent TP (mg/L)	0,9
TSS % removal	91,5
COD % removal	87,4
BOD % removal	95,7
TN % removal	86,0
TP % removal	86,6
Specific energy demand [kWh /(PE150, removed year)]	13,9
Energy kWh (m3 year)—1	0,17
Energy kWh (kg N)—1	3,6
Fe(III)/P molar ratio (Dosing only with storm events)	0,18
specific sludge production (kg/m3 treated)	0,094

power electricity generated daily from biogas (MW)	0,8
Energy self sufficiency %	0,3

Table 8-5: Osterrod performance, CAS Line vs AGS Line (Ekholm et al., 2023)

Österröd WWTP (Sweden)	CAS LINE	AGS LINE
BOD out (mg/L)	3,2	5
COD out (mg/L)	34	42,6
TN out (mg/L)	9,7	8,7
TP out (mg/L)	0,76	0,65
SS out (mg/L)	6,6	11
NH4 out (mg/L)	0,33	1,2
NO3 out (mg/L)	8,7	6,4
PO4 out (mg/L)	0,59	0,45
BOD % removal efficiency	95,8	95,7
COD % removal efficiency	83,4	85,2
TN % removal efficiency	68,7	74,4
TP % removal efficiency	74,7	80,9
TSS % removal efficiency	91,8	91,5
NH4 % removal efficiency	98,8	95,9
NO3 % removal efficiency		
PO4 % removal efficiency	65,3	71,9
specific area footprint (m2/m3/d treated)	0,62	0,3
specific volume footprint (m3/m3/d treated)	2	1,3
volumetric energy usage (kWh/m3 treated)	0,26	0,22
energy usage (kWh/PE)	0,3	0,19
chemicals usage (kg/m3 treated)	0,106	0,0489
specific sludge production (kg TS/PE)	0,12	0,13

8.3 Fixed Biomass and Hybrid Systems (BAF, TF, MBBR, IFAS)

Fixed biomass systems differ from suspended ones because the active biomass is growing attached to a support instead of flowing freely in the aqueous media. The physical support (carrier) can be moving (MBBR, IFAS), or can be still (TF, BAF, IFAS).

- BAF technology consists of a bioreactor where a biofilm develops attached to a media surface fixed in space and submerged with the wastewater flowing over it (He et al., 2017).
- In TF wastewater enters basin through a feed pipe that leads to a rotating sprinkler. The sprinkler distributes wastewater evenly over a filter bed filled with media such as rocks, gravel, or plastic materials. As the water trickles down, aeration occurs naturally through upward air movement (water academia, 2026).
- MBBR operates by cultivating a biofilm on small carrier elements that float freely throughout the reactor (water academia, 2024).

- IFAS is a hybrid between CAS and MBBR. It has a recycle from the secondary sedimentation step, to consider the suspended biomass present, and it has the carriers on which biofilm grows. Differently from MBBR, in IFAS the carriers can also be fixed.

BAF and TF processes share a lot of general features as visible in Table 8-6, while in Table 8-7 and Table 8-8 BAF and TF separate key insights are presented. MBRR and IFAS will be studied in more detail after.

Table 8-6: TF&BAF KEY FEATURES (Vatralova, 2024)

TF & BAF KEY FEATURES	(Vatralova, 2024)
PROs	smaller reactor volume due to higher concentration of biomass; minimized need for settling capacity; no need for sludge return simple mechanical configuration and rapid start up; reliable effluent quality with low energy demand
CONs	potential clogging of the filter media if inadequate screening; excessive growth could plug the media or cause free-floating media to sink; inadequate mixing or short-circuiting, resulting in inefficient use of the media; complex pipework and control systems for backwash; need of reservoirs for cleaned effluent for backwash; need of reservoirs for dirty backwash water

8.3.1 BAF

Table 8-7: BAF technology highlights

PROCESS	BAF	SOURCES
KEY FEATURES	Two main configurations: downflow with sunken media and upflow with floating media	(He et al., 2017)
	downflow BAF: advantage of better mixing; upflow BAF: ability to cope with higher influent flow rates, and can decrease odour problem	(Aniket et al., 2018)
	BAF system typically employs multiple filter cells that are rotated in and out of service as needed to accommodate varying wastewater flow rates and concentrations of organic materials	(Aniket et al., 2018)
	The bed volume below the level of air injection is undisturbed and serves as a polishing zone for the removal of suspended solids. This may eliminate the need for a separate secondary clarifier.	(Aniket et al., 2018)
	media bed has a very high specific area (> 1,000 m2/m3) and relatively low void space (35% – 40%).	(He et al., 2017)
	backwashing cycle ranging from 24 to 48 h and a backwashing time of 30 min were suitable for the domestic wastewater treatment	(Xu et al., 2022)
BNR PERFORMANCES	Denitrification can be achievement in BAF system due to the presence of anoxic microenvironments in the biofilm	(Xu et al., 2022)
	BAF demonstrated relatively poor biological phosphorus removal because of less waste sludge. Therefore, chemical phosphorus removal was considered but the accumulation of the precipitated phosphate in the filter easily caused the clogging of filter layer.	(Xu et al., 2022)
	The smaller size media offers a greater surface area per unit volume for biofilm development and minimizes the required BAF volume, but high backwash frequency is required.	(Aniket et al., 2018)
	A larger media, basically greater than 6 mm, shows a reduction in nutrient removal due to the less surface area for biofilm	(Aniket et al., 2018)
	BAF system using the smallest size media (2-4mm) gives maximum efficiency	(Aniket et al., 2018)

	BAFs with a specific surface area greater than 1,000 m2/m3 can give HRTs of less than two hours for complete nitrogen removal	(He et al., 2017)
TYPICAL APPLICATIONS	small to medium-sized treatment plants	(Vatralova, 2024)
	when land is limited	(Vatralova, 2024)

8.3.2 TF

Table 8-8: TF technology highlights

PROCESS	TF	SOURCE
KEY FEATURES	aeration occurs naturally through the chimney or stack effect; air circulates upward between the media voids due to temperature and density differences.	(water academia, 2026)
	Rotary hydraulic distribution is usually standard for this process, but fixed nozzle distributors are also being used in square or rectangular reactors.	(EPA, 2000)
	Flexibility and control are limited in comparison with activated-sludge processes.	(EPA, 2000)
	Possible ponding (surface water accumulation)	(water academia, 2026)
	biological film or slime layer (approximately 0.1 to 0.2 mm thick).	(EPA, 2000)
	Rock or slag beds can be up to 60.96 meters (200 feet) in diameter and 0.9-2.4 meters (3 to 8 feet) deep with rock size varying from 2.5-10.2 cm (1 to 4 inches).	(EPA, 2000)
	increased plastic wall thickness for medium packs that are installed in the lower section of the filter where loads increase	(EPA, 2000)
	Most rock media provide approximately 149 m2/m3 (15 sq ft/cu ft) of surface area and less than 40 percent void space.	(EPA, 2000)
	Packed plastic filters (bio-towers), on the other hand, are smaller in diameter 6 to 12 meters (20 to 40 feet) and range in depth from 4.3 to 12.2 meters (14 to 40 feet).	(EPA, 2000)
	A minimum wetting rate of 0.4 Liters per square meter-second (0.7 gal/sq ft/min) is maintained	(EPA, 2000)
	A clearance of 15.2-22.9 centimeters (6-9 inches) is needed between the bottom of the distributor arm and the top of the medium bed	(EPA, 2000)
BNR PERFORMANCES	May not meet strict treatment standards without additional stages (especially for nitrogen)	(water academia, 2026)
	Difficult to achieve BNR unless anoxic and anaerobic phases are introduced by completely flooding the TF with raw wastewater so that no voids are available for natural ventilation	(Cramer et al., 2021)
TYPICAL APPLICATIONS	low resources consumption is required and no land costraint present	(EPA, 2000)
	low skill personnel is only available	(EPA, 2000)

8.3.3 MBBR

Table 8-9: MBBR technology insights

PROCESS	MBBR	SOURCES
KEY FEATURES	immobilization of microorganisms on a carrier media reduces the microbial washout, protects them from toxic constituents, pH, and temperature extremes.	(Dutta, Sarkar, 2015)
	Carriers provide a chance to slow growing microorganisms to proliferate, irrespective of the HRT	(Dutta, Sarkar, 2015)
	carriers are buoyant and are kept in constant motion by aeration (in aerobic processes) or mechanical mixing (in anaerobic processes)	(Water & Wastewater, 2024)
	The biofilm-based approach of MBBR results in lower sludge production compared to activated sludge processes.	(Water & Wastewater, 2024)
	carriers are constantly moving within the reactor, they collide with each other and the tank walls, which sloughs off excess or dead biofilm. This "self-cleaning" mechanism ensures that the biofilm remains thin and healthy, allowing for optimal mass transfer of oxygen and nutrients to the microorganisms	(Nihao, no date)
	flow-through" system that doesn't require a clarifier or sludge recirculation,	(Nihao, no date)
BNR REQUIREMENTS	adding denitrification substrates like ethanol or methanol is a must for Anoxic MBBR.	(Levapor, 2023)
	when Bio-P reduction is required, the MBBR process is not much helpful because micro-organisms responsible for Bio-P reduction cannot be fixed on biofilms thus maintaining them in suspension is a must which requires sludge recycle	(Levapor, 2023)
TYPICAL APPLICATIONS	upgrade existing facilities to increase capacity and improve treatment efficiency without extensive civil construction.	(Water & Wastewater, 2024)
	good fit for plants with limited staff or less experienced personnel.	(Nihao, no date)

After having seen the key characteristics of MBBR technology in Table 8-9 some case studies are now given. The three case studies presented differ in nature.

Kima Aswan CAS WWTP retrofit was conventional, with MBBR modules added to aeration tanks (Table 8-10 and Table 8-11)

Lundtofte and Ryaverket case studies instead deal with the installation of MBBR modules in treatment lines more complex than the simple CAS one for what concerns nutrients removal (Table 8-12 and Table 8-13).

In fact, Kima Aswan case study shows that MBBR system implemented in a simple CAS may not be sufficient to reach nutrients removal. For this reason MBBR applications coupled with other technologies are reported with Lundtofte and Ryaverket case studies.

Table 8-10: Kima1 Aswan pre vs post upgrade treatment line (Assan et al., 2020)

INITIAL TREATMENT LINE	CHANGES DUE TO UPGRADING

21,000 m3 d 1 capacity 3 Primary sedimentation tanks 3 Aeration tanks 3 Final sedimentation tanks Contact tank 2 Thickeners 48 Sludge drying beds	30,000 m3 d 1 capacity MBBR units added to each of the aeration tanks occupying the first 40% of tank volume

Table 8-11: Kima1 Aswan pre vs post upgrade performances (Assan et al., 2020)

	INITIAL	POST UPGRADING
effluent TSS conc (mg/L)	22,75	29,5
effluent COD conc (mg/L)	68,35	52,4
effluent BOD conc (mg/L)	51,5	33
effluent TN conc (mg/L)		21,25
effluent TP conc (mg/L)		7,36
TSS % removal	91,0	88,3
COD % removal	85,0	88,5
BOD % removal	85,6	90,8
TN % removal		49,6
TP % removal		47,5
HLR (m3/m2d 1)	15,56	55 (in initial MBBR zone) and 37(in final CAS zone)

Table 8-12: Lundtofte, Biodenitro-anaerobic MBBR WWTP (Delre et al., 2019)

Lundtofte	
capacity (pe)	150 000
A/O + anaerobic MBBR secondary step	
sludge digester	
sludge incinerator present	
effluent COD conc (mg/L)	45,39
effluent BOD conc (mg/L)	5,82
effluent TN conc (mg/L)	5,65
effluent TP conc (mg/L)	0,89
COD % removal	90
BOD % removal	96
TN % removal	88

TP % removal	87
volumetric energy usage (kWh/m3 treated)	0,49
fuels consumption -heating oil, diesel,gasoline (kg/m3 treated)	0,11
ashes production from waste sludge incineration (kg/m3 treated)	0,061
total chemicals consumption (kg/m3 treated)	0,023
biogas production (Nm3/m3 treated)	0,054

Table 8-13: Ryaverket, AS + NITRIFYING TF + POST DN MBBR WWTP (Delre et al., 2019)

Ryaverket	
capacity (pe)	805 000
AS + NITRIFYING TF + POST DN MBBR secondary step	
effluent COD conc (mg/L)	40,2
effluent BOD conc (mg/L)	7,8
effluent TN conc (mg/L)	7,9
effluent TP conc (mg/L)	0,2
COD % removal	86
BOD % removal	94
TN % removal	65
TP % removal	94
volumetric energy usage (kWh/m3 treated)	0,28
fuels consumption -heating oil, diesel,gasoline (kg/m3 treated)	0,000084
heat usage (kWh/m3 treated)	0,09
wet sludge production (kg/m3 treated)	0,37
total chemicals consumption (kg/m3 treated)	0,03
heat produced through heat pump, sold (kWh/m3 treated)	2,27
biogas production (Nm3/m3 treated)	0,05

8.3.4 IFAS

Moving on, the term hybrid system usually refers to bioreactors where suspended and attached active biomass are coupled. Normally the suspended biomass configuration is modified with the introduction of carriers, either fixed or mobile. On the surface of these carriers a biofilm grows enhancing the organic matter and nutrients removal performances of the bioreactors. The new configuration is called IFAS if it possesses a sludge recycle, hybrid-MBBR if it doesn't. MBBR, born as a biofilm only system, with mobile carriers floating in a media not provided with suspended biomass, rapidly evolved into hybrid systems with also suspended biomass playing an active role and secondary settling unit added. Despite the modification, the main function in hybrid MBBR is still performed by the fixed biomass. Suspended biomass is present and can help but is not the main actor in the bioreactor. The recycle from the secondary settled sludge, even if present, is not rigorously monitored. IFAS, instead, rely almost equally on suspended and fixed biomass. This is why SRT control through RAS and MLSS is key in IFAS systems while a side-matter for the few hybrid MBBR equipped with a recycle. In Table 8-14 IFAS key principles are summarized.

Table 8-14: IFAS technology insights

PROCESS	IFAS	SOURCE
KEY FEATURES	IFAS bio-carriers can also be divided into fixed and floating; floating carriers enable enhanced mass transfer and the shedding of aging biofilm	(Wang et al., 2025)
	presence of the media often helps to create a more stable and less "slimy" sludge, which settles better in the clarifier.	(Nihao, no date)
	in IFAS a wider range of MLSS, F/M ratio conditions can be developed in the biological reactor compared to CAS	(Levapor, 2023)
	bioreactor carriers filling rate must be kept below 70%	(Wang et al., 2025)
	mixing energy provided by the aeration system is critical for sloughing of biomass and the creation of a thin biofilm	(Hazen and Sawyer, no date)
	If a retrofit is evaluated, the existing aeration capacity needs to be evaluated to determine whether it is adequate for the increased BOD removal and biomass respiration expected.	(SSWM, 2020)
	Highly mechanised system requiring expert design, operation and maintenance as well as mechanical spare parts. Large energy requirements necessary.	(SSWM, 2020)
	the treatment cost per pound of NH3-N removed per day in a fixed media IFAS system is approximately 1/3 less than in a dispersed media IFAS system.	(SSWM, 2020)
BNR REQUIREMENTS	Denitrification process can be designed with suspended biomass and without the addition of any MBBR media or readily available substrate for denitrification.	(Levapor, 2023)
	IFAS process can be configured for Bio-P reduction with conventional process concepts like A2O or Bardenpho process as utilized with activated sludge process.	(Levapor, 2023)
	biofilm sludge has a longer SRT than suspended sludge. High SRT of nitrogen removal bacteria in attached sludge and the low SRT of phosphorus accumulating bacteria in suspended sludge	(Wang et al., 2025)
	attached biomass provides much of the nitrification activity during colder temperatures. Nitrification with less than 50 percent of the volume required for a conventional system.	(Hazen and Sawyer, no date)
	contribution of ANAMMOX to the total nitrogen removal efficiency can reach 44-48%	(Wang et al., 2025)
TYPICAL APPLICATIONS	designed to handle the high, sudden flows typical of CSOs, providing an effective and compact solution for treating surges before discharge.	(Nihao, no date)
	powerful solution for plants with stringent environmental regulations when enhanced performance, particularly for nutrient removal, is non-negotiable	(Nihao, no date)

The following two case studies refer to a retrofit and a In Table 8-15 a retrofit case study (Narragansett bay) is presented highlighting the main interventions required to install an IFAS system in a CAS WWTP. In Table 8-16, instead the performances of an IFAS WWTP (Vaxjo) are shown. Apparently, the resources consumption of Vaxjo WWTP is very high for the N removal achieved questioning the suitability of the IFAS process. The lack of a relevant number of studies makes it hard however to determine the effectiveness of the IFAS process in general.

Table 8-15: Narragansett bay pre vs post upgrade comparison (Wilson et al., 2012)

INITIAL TREATMENT LINE	CHANGES DUE TO UPGRADING
existing preliminary treatment	
primary clarification PLOW: 4 units	
10 CAS reactors	replace the 10 CAS reactors with 10 IFAS reactors with anoxic zones
9 secondary clarification RSR units	construction of building for supplemental alcalinity for nitrification
existing tertiary treatment	construction of building for supplemental C for denitrification
existing sludge treatment	centrifugal blowers converted to turboblowers to satisfy extra O2 demand

Table 8-16: Vaxjo, IFAS WWTP (Delre et al., 2019)

Vaxjo	
capacity (pe)	95 000
IFAS (AS+HYBAS) secondary treatment	
side deammonification	
sludge thermal hydrolisis pre digestion	
effluent COD conc (mg/L)	40,1
effluent TN conc (mg/L)	12,3
effluent TP conc (mg/L)	0,088
COD % removal	90
TN % removal	66
TP % removal	98
volumetric energy usage (kWh/m3 treated)	0,66
fuels consumption -heating oil, diesel,gasoline (kg/m3 treated)	0,002
wet sludge production (kg/m3 treated)	0,91
dry sludge production (kg/m3 treated)	0,24
total chemicals consumption (kg/m3 treated)	0,13
biogas production (Nm3/m3 treated)	0,15

8.4 Advanced Membrane Solutions (MABR, MBR)

8.4.1 MABR

Membrane Aerated Bio Reactors were conceived as fixed biomass systems where the carrier was a membrane instead of a simple support. MABRs, however, must not be confused with MBRs. In fact, the membrane role it's not to filter in MABR, but to support the biofilm while providing oxygen. The concept is closer to an MBBR than to an MBR. In MBR in fact the biomass is essentially suspended, and the membrane function is to filter and not to support the biomass. The full-scale application of MABRs rapidly evolved towards an hybrid configuration where the MABR module is installed in anoxic tanks with suspended denitrifying biomass (with P accumulating biomass in anaerobic pockets) cooperating with the autotroph nitrifying and the COD oxidizing biofilm growing on the membranes.

Table 8-17: MABR Key insights

PROCESS	MABR	SOURCES
KEY FEATURES	self-respiring membrane envelope that passively delivers oxygen directly into the aerobic bacterial biofilm while anaerobic bacteria flourish in the anoxic environment of the rest of tank.	(Fluence, 2026)
	Counter current oxygen-substrate supply to the biofilm to overcome mass transfer issues due to biofilm thickness	(Dominici, Ruffino, 2020)
	Higher surface roughness and positive charge of membrane favour biofilm attachment and development	(Dominici, Ruffino, 2020)
	in the external side of the biofilm anaerobic microorganism develop, in the middle of the biofilm heterotroph anoxic microorganisms thrive while in the inner side of the biofilm autotroph aerobic microorganisms proliferate	(Dominici, Ruffino, 2020)
	The pressure at which oxygen is supplied from the membrane influences the mass transfer velocity; if the pressure is too high oxygen reaches the outer layers of the biofilm impeding the formation of the required anoxic and anaerobic zones and gas bubbles may form lowering OTE	(Dominici, Ruffino, 2020)
	The liquid layer at the outer biofilm raw bulk interface represents the main resistance to mass transfer. Providing oxygen from the membrane increases oxygen transfer efficiency avoiding the need to pass through the liquid outer biofilm layer, moreover the biofilm-bulk liquid interface helps in retaining the supplied oxygen in the biofilm	(Dominici, Ruffino, 2020)
	biofilm thickness between 600µm e 1200µm with optimum around 1000 µm	(Dominici, Ruffino, 2020)
	possible to achieve 85% aeration energy consumption reduction compared to CAS	(Dominici, Ruffino, 2020)
	MABR applications reach steady-state conditions after 60 – 120 days of operation	(Dicataldo et al., 2025)
	SAE of 6,5-14 kgO2/kWh compared to fine bubble diffusers SAE of 2,5-6 kgO2/kWh and coarse bubble diffusers SAE of 1,2-3 kgO2/kWh	(Galletti, 2020)
	OTE is around 100% while in CAS oscillates between 15 and 40 % while sludge production in MABR is lower than 0.2 kgTSS kg-1COD	(Dominici, Ruffino, 2020)
BNR REQUIREMENTS	optimum influent COD/TN around 5	
	optimal pH around 7.95, allowed range for pH: 7-9.	
TYPICAL APPLICATIONS	increase nutrient removal and capacity treatment of existing facilities with limited land availability	(Dominici, Ruffino, 2020)
	Industrial wastewater treatment	(Dicataldo et al., 2025)

After having seen MABR principles in Table 8-17 a case study reporting a MABR retrofit in a CAS Canadian WWTP is reported in Table 8-18 and Table 8-19. Significant changes appear in energy consumption and N removal. As in all other circumstances the need of a wider dataset is evident to evaluate properly the pro and cons of these retrofit.

Table 8-18: Canada CAS to hybrid MABR upgrade (Lakshminarasimman, Parker, 2025)

INITIAL TREATMENT LINE	CHANGES DUE TO UPGRADING
average capacity of 9320 m3/d preliminary treatment with 2 mm fine screens and grit removal	added MABR in upstream anoxic tank with return activated sludge recycled to it.
CAS process consists of two aeration tanks after aeration coagulants for chemical phosphorus removal.	MABR tank has four parallel treatment trains (each 21.4 m long × 2.4 m wide × 3.1 m deep) with a tot 637 m3 volume in each train yielding a total membrane surface area of 69,120 m 2
Three secondary clarifiers	specific surface area of 109 m2/m3 .
disinfection with Cl	

Table 8-19: Canada CAS vs hybrid MABR performances (Lakshminarasimman, Parker, 2025)

Canada	INITIAL	POST UPGRADING
effluent BOD conc (mg/L)	7	7
effluent TN conc (mg/L)	15-35	10-20
effluent TP conc (mg/L)	<0,5	<0,5
BOD % removal	96	96
TN % removal	45-60	75-90
TP % removal		
volumetric energy usage (kWh/m3 treated)	0,37	0,17
aeration efficiency (kg O2/ kWh)	0,83	2,7
sludge generation		no observable change in solids generation
rough estimate Alum dosage (L/d)	1200	no observable change
rough estimate Alum dosage (kg/m3)	0,17	no observable change

8.4.2 MBR

Being aware of the relationship between MLSS content in bioreactor and organic matter and nutrients removal performance, MBR systems rise to the attention. Membrane Bio Reactors represent a viable solution for WWTPs trying to increase the operative MLSS without overloading clarifiers. Using membranes allows to overcome the need for a secondary settling tank in most of the cases. Some pathogens, according to membrane pore sizes, can be removed too, lowering the load sent to a disinfection unit. These advantages come at the cost of increased chemicals and energy consumption. Frequent maintenance and replacement of membrane modules is required too.

A resume of the characteristics of MBR systems is provided in Table 8-20.

Table 8-20: MBR insights

PROCESS	MBR	SOURCES
KEY FEATURES	two basic configurations: hollow fiber bundles and plate membranes.	(EPA, 2007)
	Hollow fibers membranes are made up of bundles of very thin straw-like fibers. Flat sheet membranes are like book pages —thin polymer films on a support layer	(Oxymo, 2025)
	MBR systems require some degree of pumping/suction to force the water flowing through the membrane; the advantage of using pressure is that throughput can be controlled	(EPA, 2007)
	alternative is to draw a vacuum through the membranes. The advantage of the vacuum is that it is gentler to the membrane	(EPA, 2007)
	operational flexibility with respect to flow rates thanks to the possibility of readily adding or subtracting units as conditions dictate	(EPA, 2007)
	complete separation of hydraulic retention time (HRT) and solid retention time (SRT). Lower production of surplus activated sludge (if operate at higher SRT)	(Vaccari et al., 2022)
	Hollow Fiber: More prone to internal pore blocking; Flat Sheet: Surface fouling predominant	(Oxymo, 2025)
	Average specific surface area is reported to be 292 m2/m3 and 118 m2/m3 for commercial hollow-fiber and flat-sheet membranes	(Vaccari et al., 2022)
	For maintenance requirements is recommended that the installation include one additional membrane tank/unit beyond what the design would nominally call for.	(EPA, 2007)
	Prevalent use of hollow-fiber membranes for larger installations peak design flows should be no more than 1.5 to 2 times the average design flow.	(EPA, 2007)
	require 1- to 3-mm-cutoff fine screens immediately before the membranes	(EPA, 2007)
	Membranes typically require that the water surface be maintained above a minimum elevation so that the membranes remain wet during operation	(EPA, 2007)
	50% higher operating costs compared to CAS	(Vaccari et al., 2022)
	amount of air needed for the scouring has been reported to be twice that needed to maintain aeration in a conventional activated sludge system	(EPA, 2007)
	Otherwise back-pulsing technique, in which permeate is occasionally pumped back to keep the pores cleared. Time of pulsing accounting for 1 to 5 percent of the total operating time.	(EPA, 2007)
	Typical permeate flux ranges: Hollow Fiber UF: 50–150 L/m²·h; Flat Sheet UF: 40–120 L/m²·h	(Oxymo, 2025)
	Hollow Fiber: pressures of 0.1 to 0.3 bar are used for UF and 0.02 to 0.1 bar for MF. Flat Sheet TMP: 0.2–0.4 bar (UF), slightly higher due to flow channel resistance	(Oxymo, 2025)
	Hollow Fiber: Lightweight modules (<50 kg), quick-swap design. Single fiber failure rarely impacts overall performance. Flat Sheet: Heavier cassettes (50–200 kg), often require hoists. A torn sheet necessitates full cassette replacement.	(Oxymo, 2025)
	Hollow Fiber: Backwash cycles: 5–15 minutes every 15–30 minutes of operation; Air scouring: 5–10% air-to-water ratio to disrupt fouling layer	(Oxymo, 2025)
TYPICAL APPLICATIONS	will to automate the process (especially in industrial sector)	(Vaccari et al., 2022)

	for medium-sized wastewater treatment plants (WWTPs) having capacity between 10,000 and 100,000 PE	(Vaccari et al., 2022)

In Table 8-21 and Table 8-22 a SBR retrofit is presented, while in Table 8-23 and Table 8-24 a CAS retrofit will be shown. The results show great nutrients removal performances.

Table 8-21: Dundee, SBR upgrade to MBR (Simon Judd and Claire Judd, 2011)

SBR to MBR
4 tanks built
100 % increase in capacity
40 mg/L alum for P removal
retrofit cost 6,55 million $ (2005)
electricity cost (+100%)
solids handling cost (-35%)
Cleaning through soaking in >5000 mg/L hypochlorite for >2 h periodically followed by a 300 mg/L mineral acid soak
0,66-2,99 kWh/m3 energy consumption
flux setpoints of 20 and 32 LMH
air scour intensity of approximately 0.27 Nm3/(m2 h)

Table 8-22: Dundee, SBR vs MBR effluent comparison (Simon Judd and Claire Judd, 2011)

Effluent	SBR
COD (mg/L)	11,9
TSS (mg/L)	15,9
NH4 (mg/L)	6
TN (mg/L)	
TP (mg/L)	0,77
Effluent	MBR
COD (mg/L)	1
TSS (mg/L)	0,4
NH4 (mg/L)	0,2
TN (mg/L)	
TP (mg/L)	0,12

Table 8-23: Kupfer, CAS upgrade to MBR (Simon Judd and Claire Judd, 2011)

Kupfer, Germany (CAS to MBR)
100 m3/h peak hourly flow
total membrane surface of 7200 m2
MLSS concentration of around 5 g/L in the aerobic tank and 7 g/L in the membrane tank
net flux of 8 LMH
cycle of 9 min filtration and 1 min relaxation

SADm of 0.25 m3/(m2h) nSADp of 42 TMP ranges from 20 to 400 mbar permeability of 100-780 LMH/bar membrane is cleaned once a year with 500 mg/L hypochlorite and 500 mg/L citric acid, with a downtime of 24 h per clean

Table 8-24: Kupfer, MBR effluent (Simon Judd and Claire Judd, 2011)

Effluent (m3/d)	7274
COD (mg/L)	30
BOD (mg/L)	3
TN (mg/L)	5
TP (mg/L)	0,2
COD % rem	98
BOD % rem	99,7
TN % rem	95,5
TP % rem	99,2

8.5 Economic Order of Magnitude of the investments required to retrofit WWTPs not suitable to implement Biological Nutrients Removal

The chapter has focused on the available technologies for those WWTPs which for some reason may not afford to rely mainly on biological nutrients removal. To end this part some case studies will be briefly illustrated to get an estimate of the investments required to make these WWTPs compliant to the new standards either by implementing one or more of these alternative technologies or going through a substantial reconstruction process. A quick comparison will be then done with the investments required to implement a heavily based biological process to tackle nutrients removal obtained in the previous chapter (7.5). The same uncertainties on the trustability of the investments reported in that context apply also here. The values below presented should be taken only as order of magnitude guesses.

8.5.1 Investments to retrofit WWTPs not satisfying the requirements to rely mainly on biological nutrients removal, with advanced technologies (IFAS, MBR, AGS, MABR):

Sacyr Water reports to plan the upgrade of Huelva WWTP (*IDRA*, 2026). Foreseen interventions are expanding the pumping station to manage stormwater events, renovating equipment and pipes, converting existing biological reactors to IFAS and adding an additional sludge line equipped with a thermal hydrolysis unit. (*IDOM*, 2025)

Table 8-25: Huelva CAS WWTP retrofit

WWTP	Huelva, Spain (retrofitted to IFAS)
SIZE (PE)	180000
VOLUME CAPACITY (m3/d)	48538
TREATED VOLUME (m3/d)	32500
INITIAL CONFIGURATION	CAS

CAPEX (euros)	36300000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	27
RETROFIT YEAR START	2026
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,19

Cape Town CAS WWTP (*City of Capetown*, 2023) is going through major expansions and renovations including: new inlet works, membrane bioreactor (MBR) treatment module, raw sewage pump station, process control facility, quaternary treatment and ponds dredging (*Central Dredging Association*, 2023)

Table 8-26: Potsdam, South Africa, WWTP retrofit

WWTP	Potsdam, South Africa (retrofitted to MBR)
SIZE (PE)	
OLD VOLUME CAPACITY (m3/d)	47000
NEW VOLUME CAPACITY (m3/d)	100000
INITIAL CONFIGURATION	CAS
CAPEX (euros)	227000000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	44
RETROFIT YEAR START	2023
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,36

MBR retrofit was the choice also for Avilà WWTP which had no need to enlarge its land footprint this way (*Pollution Solutions*, 2013), (*Cameto*, 2015). A 10 years depreciation time was chosen due to the nature of the retrofit.

Table 8-27: Avilà WWTP retrofit

WWTP	Avilà, Spain (retrofitted to MBR)
SIZE (PE)	190000
NEW SIZE (PE)	327000
NEW VOLUME CAPACITY (m3/d)	35000
INITIAL CONFIGURATION	CAS ?
CAPEX (euros)	15000000
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	
RETROFIT YEAR START	2013
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,12

Kloten Opfikon WWTP was retrofitted and expanded through the construction of an AGS line. Meanwhile it also added quaternary treatment and renewed energy production facilities through photovoltaic panels and biogas production (*HFS*, 2025). Data on the project reported in

Table 8-28 sourced from (*AKO*, 2025).

Table 8-28: Kloten-Opfikon WWTP retrofit

WWTP	Kloten-Opfikon, Switzerland (retrofitted to AGS)
SIZE (PE)	54000
NEW SIZE (PE)	125000
VOLUME CAPACITY (m3/year)	6442655
TREATED VOLUME (m3/d)	
INITIAL CONFIGURATION	A2/O ?
CAPEX (euros)	97297297,3
OPEX (euros/year)	
TIME REQUIRED FOR THE RETROFIT (months)	96
RETROFIT YEAR START	2017
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,94

North Toronto WWTP opted for a MABR retrofit to upgrade the existing nutrients removal section. The initial retrofit involved just one of the four treatment lines available but still provided valuable insights into the feasibility of the modification (Veolia, 2024)

Due to the nature of the retrofit the Capex were divided over a 10 years span.

Table 8-29: North Toronto WWTP retrofit

WWTP	North Toronto, Canada (retrofitted to MABR)
SIZE (PE)	
NEW SIZE (PE)	
VOLUME CAPACITY (m3/d)	45500
TREATED VOLUME (m3/d)	11400
INITIAL CONFIGURATION	CAS + chemical P removal and disinfection
CAPEX (euros)	9501804
OPEX (euros/year)	462150
TIME REQUIRED FOR THE RETROFIT (months)	2
RETROFIT YEAR START	2024

SPECIFIC INVESTMENTS COSTS (euros/m3)	0,34

8.5.2 Investments to rebuild from scratch WWTPs to achieve the new standards:

Retrofitting existing WWTPs has been the priority when considering the available technologies to improve nutrients removal. To complete the picture some studies reporting newly built WWTPs adopting modern processes to tackle nutrients pollution are presented so that the investments required can be compared with the retrofitting costs estimations.

Sacyr will build the Orotava WWTP, whose nutrients removal step will rely on a MBR system (*IDRA*, 2026).

Table 8-30: Orotava WWTP construction

WWTP	Orotava, Spain
SIZE (PE)	100000
SECONDARY TREATMENT VOLUME CAPACITY (m3/d)	20000
PRIMARY TREATMENT VOLUME CAPACITY (m3/d)	10000
CONFIGURATION	MBR
CAPEX (euros)	17500000
OPEX (euros/year)	
TIME REQUIRED FOR THE CONSTRUCTION (months)	37
CONSTRUCTION YEAR START	2026
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,30

Veolia has built a new WWTP in Lille, with separate stormwater management line, hybas biological process and thermal hydrolysis unit prior to anaerobic digestion to increase biogas production and reduce waste sludge disposal. (*Wastewater Digest*, 2010)

Table 8-31: Marquette-lez Lille WWTP reconstruction

WWTP	Marquette-lez Lille, France
SIZE (PE)	620000
LAND REQUIREMENTS (m2)	150000
TREATMENT VOLUME CAPACITY (m3/d)	241920
CONFIGURATION	IFAS
CAPEX (euros)	75000000
OPEX (euros/year)	4666666
TIME REQUIRED FOR THE CONSTRUCTION (months)	48
CONSTRUCTION YEAR START	2011
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,11

Always in Lille, SAUR has begun the construction of the new Wattrelos WWTP. Compared to the existing one the capacity will be expanded, a new rainfall management system, ambitious energy self-sufficiency plans, and wastewater reuse are announced. Unfortunately no info on the kind of bioreactor and on the land requirements was available. (*NGE*, no date)

Table 8-32: Wattrelos WWTP reconstruction

WWTP	Wattrelos, Lille, France
SIZE (PE)	417000
NEW SIZE (PE)	511500
TREATMENT VOLUME CAPACITY (m3/d)	285120
CONFIGURATION	
CAPEX (euros)	200000000
OPEX (euros/year)	7750000
TIME REQUIRED FOR THE CONSTRUCTION (months)	72
CONSTRUCTION YEAR START	2025
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,19

Trento has completed the construction of its third WWTP. It aims at 30% energy self-sufficiency thanks to photovoltaic, turbine installation on effluent and cogeneration unit from biogas. Works were slowed down due to COVID-19 pandemic (*Ufficio stampa Trento*, 2023).

Table 8-33: Trento WWTP construction

WWTP	Trento 3, Italy
SIZE (PE)	150000
LAND REQUIREMENTS (m2)	
TREATMENT VOLUME CAPACITY (m3/d)	48000
CONFIGURATION	A/O
CAPEX (euros)	115000000
OPEX (euros/year)	
TIME REQUIRED FOR THE CONSTRUCTION (months)	60
CONSTRUCTION YEAR START	2018
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,41

As a last note in

Table 8-34 and Table 8-35 are reported the investments required to build two new WWTPs based on AGS technology (*Nereda Haskoning*, no date). The investments vary considerably in the two cases making it difficult to assess if retrofitting an existing WWTP with an AGS technology is cheaper than directly rebuilding it.

An analysis of the performances of retrofitted WWTPs compared to those of brand new WWTPs should be conducted. As already mentioned not considering the real performances of the WWTPs makes the conclusions drawn here quite weak.

Table 8-34: Cork Lower Harbour WWTP construction

WWTP	Cork lower habour
SIZE (PE)	65000
VOLUME CAPACITY (m3/d)	14625
USED VOLUME CAPACITY (m3/d)	
CONFIGURATION	AGS
CAPEX (euros)	135000000
OPEX (euros/year)	
TIME REQUIRED FOR THE CONSTRUCTION (months)	
CONSTRUCTION YEAR START	
SPECIFIC INVESTMENTS COSTS (euros/m3)	1,58

Table 8-35: Utrecht WWTP construction

WWTP	Utrecht
SIZE (PE)	430000
VOLUME CAPACITY (m3/d)	76271
USED VOLUME CAPACITY (m3/d)	
CONFIGURATION	AGS
CAPEX (euros)	120000000
OPEX (euros/year)	
TIME REQUIRED FOR THE CONSTRUCTION (months)	
CONSTRUCTION YEAR START	2017
SPECIFIC INVESTMENTS COSTS (euros/m3)	0,27

9 Conclusion and Recommendations

A. Key points of the work

The work has shown that a considerable fraction of the Portuguese WWTPs should be retrofitted to enhance their nutrients removal performances.

After having excluded from the analysis the WWTPs below the 2000 pe design capacity threshold,108 WWTPs over the existing 529 reported, having the capacity to deal with 68,6% of the national load, have been proved to be in the need of a retrofit according to the new Directive. (

Table 4-5)

Of these 108 WWTPs, 68 treatment plants, having the capacity to treat 54,8% of the national load, share a very similar bioreactor, with a continuous flow, either in a plug flow or CSTR regime, and with suspended biomass playing the key role of pollutants degradation. (in these 68, 7 WWTPs, still achieving just primary level of treatment, were included)

It has been decided to look at these 68 WWTPs as at the most representative sample for the starting situation of Portuguese WWTPs needing a nutrients removal retrofit. (Table 5-5)

A group of reference Danish WWTPs, already satisfying the new requirements for nutrients removal, was used to set a standard to aspire to (pag.133)

An analysis of the water line schemes of these reference Danish WWTPs revealed that they often relied heavily on a BNR process happening in a continuous suspended biomass bioreactor, with the greatest nutrients load removed biologically.

Chemical and physical processes, even if often present, as well as advanced online monitoring of the overall process, played a complementary function, being more a refinement step than a core one.

This Danish standard has been chosen as a possible strategy to retrofit the 68 Portuguese WWTPs of interest, which represent a considerable fraction of the Portuguese WWTPs requiring an upgrade.

An evaluation of the key requirements to fulfil to be able to successfully implement in the Portuguese context a process relying principally on biological nutrients removal has been carried out.

Bioreactor’s influent characteristics (pH, alkalinity, temperature, C/N, C/P) and the possible need of influent preparations steps to make it suitable for a BNR process (equalization tanks, chemicals storage and addition systems, fermentation tanks etc) have been highlighted as the key obstacles to overcome together with guaranteeing adequate SRT for the biomass to adapt and proliferate (paragraph 7.2).

Despite the probable difficulties Portuguese would face if trying to replicate the Danish strategy the results obtained by the latter would seem to pay off.

In fact, a comparison of the performances (when found) of the reference Danish WWTPs and of the Portuguese sample has shown:

- evident superior effluent quality
- lower energy consumption on a volumetric basis

- lower sludge production both on a nutrient removal mass basis and on a volumetric basis.

A chemicals consumption direct comparison was not possible whereas a reasonable superior land demand for the Danish systems has been observed (paragraph 6.5).

The uncertainty associated with the trustability of the performance data retrieved, the limited sample size, and the understandable difficulty in assessing the possibility to rely on a BNR process in the Portuguese context, limit a lot the use of these results.

However, picturing as feasible a retrofit based on the Danish model three scenarios have been considered in paragraph 7.5.

- The WWTP can implement a BNR process and rely mainly on it
- The core of the WWTP cannot be retrofitted but upgrade of auxiliary treatment steps and infrastructure can happen and still impact overall nutrients removal performances
- The WWTP already achieves nutrients removal but its performances must be updated

A comparison of the investments required to adapt to the new standards in terms of nutrients removal according to the starting scenario was then performed. Again great uncertainties on the quality of the retrieved data, combined with the little quantity of data found, limit considerably the trustability of the estimations.

For those WWTPs instead, not able to satisfy the requirements to implement a BNR as a core step in their process scheme, various alternative solutions have been studied in chapter 8.

The two main scenarios considered in paragraph 8.5 were:

- The WWTP can be retrofitted by implementing one among IFAS, MBR, AGS ,MABR technologies
- The WWTP cannot be retrofitted and need to be rebuilt, its nutrients removal step will be based on alternative technologies (IFAS, MBR, AGS ,MABR)

Putting together the results from paragraph 7.5 and paragraph 8.5 a totality of 5 scenarios of investment emerged:

- Investments to retrofit CAS WWTPs introducing a nutrients removal unit following Danish example (A2/O or A/O + chem P removal)
- Investments to retrofit CAS WWTPs introducing an alternative nutrients removal unit (IFAS, MBR)
- Investments to rebuild from scratch WWTPs to achieve the new standards
- Investments to enhance nutrients removal (and general performances) of WWTPs that already implement nutrients removal
- Investments to enhance nutrients removal (and general performances) focusing on infrastructure different from bioreactor (secondary sedimentation, sewer system, stormwater management, control system)

From Table 9-1 it seems that retrofitting maximising the function of biological processes (A2/O or A/O + chem P removal) is more cost effective than rebuilding from scratch or than retrofitting relying on advanced technologies (IFAS, MBR, AGS, MABR). The results point towards retrofitting WWTPs maximizing existing infrastructure usage and biological role in nutrients removal to reduce costs. Working on infrastructure different from the bioreactor could still lead to improvements in performances with considerably lower investments requirements.

Table 9-1: Retrofitting investments specific costs

Investment type	Range (euros-m3 treated)
Investments to enhance nutrients removal (and general performances) focusing on auxiliary infrastructure	0,008-0,012
Investments to retrofit CAS WWTPs on Danish example	0,0017-0,14
Investments to enhance nutrients removal (and general performances) of WWTPs that already implement nutrients removal	0,1
Investments to retrofit CAS WWTPs introducing an alternative nutrients removal unit (IFAS, MBR, AGS, MABR)	0,12-0,94
Investments to rebuild from scratch WWTPs to achieve the new standards	0,11-1,58

A final remark is that all investments categories with more than one case study considered, show orders of magnitude variability within the predicted specific costs, jeopardising the initial intent of achieving at least an order of magnitude guess of the costs.

This certifies that the sample size again is too little to derive meaningful averages hindering to understand if a value should be seen as an outlier or not.

Another conclusion that can be drawn is that each WWTP possess a high degree of uniqueness and it could be quite difficult to group WWTPs just based on the core process adopted in the (bio)reactor step. Influent type, geographical location, configuration of the upstream and downstream treatment steps with respect to the bioreactor play a great role, in determining both performances and investments costs.

B. Future work to be done

Many of the key factors that contribute in making the Danish systems so successful, have been overlooked in this work.

Some of them are mentioned here stating the need for further studies to understand their impact in the Portuguese context:

- extensive sensor network and online control of the overall process
- extensive automation of the modification of operative strategies according to real time conditions
- containment tanks for stormwater events
- high fraction of separate sewer systems
- Separate treatment line for rainwaters
- WWTPs Digital twin use to simulate new configurations prior to their implementation

These factors undoubtedly play a crucial role in assuring biological treatment efficiency and deserve special attention. A quick recap of the motivations for that follows:

- Constantly swinging operative conditions, common in the real world, together with increased risks of WWTPs flooding due to heavy rain periods, complicate the achievement of high treatment efficiencies.
- Maximizing existing infrastructure usage and biological role in nutrients removal to reduce costs and resource consumption represent a crucial turning point for the future of many existing WWTPs.
- Having the possibility to foresee the effects of a change in the operative strategy before implementing it could save large amounts of time and resources.

These are only some of the reasons why the above-mentioned factors should be carefully evaluated. Their role in determining the overall efficiency of a WWTP should not be underestimated.

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1 Appendix – Data processing and databases creation

1.1 EU dataset source

EU publishes on EEA page, (European Environment Agency) downloadable datasets containing information coming from member states compulsory reporting activity on topics related to wastewater management.

The file the analysis of chapter 4 is based on was downloaded in November 2025 and it was called CSV, as the format it was originally saved in. The file contained 12 sheets.

The used sheets were only two. Sheet UWWTPS and sheet DischargePoints.

Unfortunately it is not easy to retrieve it online. The EEA folder containing the dataset is often moved or updated with new material and sometimes it might be difficult to access twice the same folder.

At the time of writing the thesis, March 2026, the EEA page where the used CSV excel file was found, contains among others a folder called CSV and a file called Waterbase_UWWTD_13thCall_final.

The CSV folder contains 19 downloadable CSV files. 12 of these 19 correspond to a messy version of the sheets of the CSV file downloaded in November 2025. Data in these sheets are hardly usable since they are, for each row, compressed in one cell instead of being distributed between various columns.

Instead, the file called Waterbase_UWWTD_13thCall_final, is essentially the CSV file the analysis of chapter 4 was based on.

One important difference is that it is made of 13 sheets instead of 12. The extra one, ReceivingAreas_SAMain, contains information on the sensitive areas.

At the time the CSV file was downloaded this sheet wasn't there and obviously the determination of sensitive areas was made differently than what could have been if having this sheet available.

ReceivingAreas_SAMain sheet, unavailable in November 2025, names sensitive or less sensitive areas and associates to them a code identifying the kind of sensitive area it is through column rcaZType.

ReceivingAreas_SAMain sheet also highlights the sensitivity to N or P or other pollutants through columns rcaParameterM, rcaParameterN, rcaParameterP, rcaParameterOther.

Table 1-1: rcaZType code list

	rcaZType code list
UWW55CMSA	sensitive area outside/downstream of a catchment
UWWCASA	coast area sensitive area
UWWCLSA	coastline sensitive area
UWWCMSA	sensitive area inside the catchment
UWWLKSA	lake sensitive area

UWWRISA	river sensitive area
UWWTWSA	transitional water sensitive area

Table 1-2: rcaParameter code list

	rcaParameter code list
rcaParameterN	N eutrophic sensitive area
rcaParameterP	P eutrophic sensitive area
rcaParameterOther	sensitive area for other reasons
rcaParameterM	microbiological sensitive area

1.2 Determination of the sensitive discharge areas

All the 529 Portuguese WWTPs initially present in the November 2025 downloaded UWWTPS sheet of CSV file were considered, filtering them out through the column “rptMStateKey_perfData” where “PT” was selected.

Treatment plants with a design capacity under 10 000 pe, selected through the column “uwwCapacity” where immediately excluded from the group of WWTPs requiring retrofit. Treatment plants with a design capacity over 150 000 pe were immediately included in the retrofit-required group.

The classification of the discharge points for the treatment plants with a design capacity between 10 000 and 150 000 pe was then analysed.

To do it, sheet UWWTPS and sheet DischargePoints were combined, creating one single sheet made of the concatenation of the two. To guide the merging process uwwName column for the UWWTPS sheet, and dcpName column for the DischargePoints sheet were used. Rows of the DischargePoints sheet showing the same entry in the column dcpName, of the rows of the UWWTPS sheet in the column uwwName, were concatenated.

The resulting unique sheet was called merged_output_debug.

From now on the work will refer to this merged_output_debug file every time it mentions the original dataset, since this was born from the concatenation of two untouched sheets of the downloaded CSV file.

Column dcpTypeOfReceivingArea of merged_output_debug file was used to determine if a WWTP was discharging in a sensitive area.

Table 1-3: Type of receiving areas codelist

	Type of receiving areas code list
CSA	Catchment sensitive areas ad defined in article 5.5 of UWWTD
NA	Normal area
LSA	Less sensitive area

A523	eutrophication risk area as defined in article 5.2 and 5.3 of UWWTD

In this work less sensitive areas and catchment sensitive areas were considered as sensitive as A523 areas to work in a conservative scenario.

Every WWTP discharging in area different from NA was labelled as having a sensitive discharge point.

One could have argued that it would have been a better idea to classify the sensitiveness of a receiving area according to merged_output_debug column rcaCode, (sourcing from DischargePoint sheet) instead of using column dcpTypeOfReceivingArea.

The result would have been the same.

In fact, as said in (Eionet, DataDictionary, 2021), every discharge area labelled in sheet DischargePoints differently from NA, should have its rcaCode column entry filled with a code identifying a sensitive or less sensitive area and then included in the sheet ReceivingAreas_SAMain.

In other words all areas different from NA should be considered sensitive.

1.3 Construction procedure of the datasets used in chapters 4,5,6,7

The approach of adding columns to the original file was repeated many other times to work more fluently during the grouping process of chapter 4.

A column named “Range dimensionale” was included to label WWTPs according to design capacity in three categories: low, medium, high.

Table 1-4: Design size capacity range legend

	Design capacity size range (pe)
low	<10 000
medium	10 000-150 000
high	>150 000

Medium size WWTPs discharging in sensitive points were included in the list of treatment plants the thesis focuses on together with all high size WWTPs. The rest of medium size WWTPs and all low ones were discarded.

In total 108 Portuguese WWTPs to retrofit were identified.

To simplify the analysis of the treatment steps adopted by WWTPs two columns were added to the original dataset, filtration and disinfection. Filtration level was attributed to each WWTP showing at least one between sand filtration and microfiltration, Disinfection level was attributed to each WWTP showing at least one between Chlorination, UV and Ozonation. This condensation was done since filtration and disinfection step aren’t particularly relevant when dealing with nutrients removal so there was no need to have great detail around them.

Treatment plants were then grouped according to the level of treatment achieved. To do so another column, named uwwLevelofTreatment was added to the original dataset. More stringent level of treatment was attributed to each WWTP that beyond secondary level showed at least one step between N removal, P removal, Disinfection and Filtration.

More stringent level WWTPs were then analysed in terms of N removal and P removal units.

At the end of chapter 4 analysis all the 108 rows of the dataset relative to Portuguese WWTPs that require retrofit (with all the columns added during chapter 4) were extracted to form the basis of the subsequent database used and expanded with the developing of chapter 5.

Chapter 5 web search to identify the waterline sequences of Portuguese WWTPs to retrofit belonging to priority group was conducted studying one single WWTP at a time.

Entries from uwwNUTS, uwwCode and uwwName were taken from the dataset and often searched together with “etar”, “scheme”, “thesis” and “WWTP” keywords.

Aguas de Portugal (AdP) official web pages were used as first sources when available.

Local online press articles, environmental impact studies, construction engineering companies websites and thesis from main Portuguese repositories completed the list of main sources.

Table 1-5: Portuguese thesis main repositories

list of main Portuguese thesis repositories
RCAAP RUN Repositorio Ulisboa ESTESC Repositorio aberto da universidade de Porto

In Table 1-6 a list of the thesis and reports mainly used to derive Portuguese to retrofit WWTPs characterization is given.

Table 1-6: Documents sources for Portuguese WWTPs to retrofit characterization

WWTP	TITLE	AUTHOR	YEAR	TYPE OF DOCUMENT
Agra; Lordelo; Rabada: Serzedelo	MASTER PLAN PARA A PROMOÇÃO DO AVE CAPITAL VERDE EUROPEIA		2014	Report
Alcantara	OTIMIZAÇÃO DA ETAPA DE DESIDRATAÇÃO DA FÁBRICA DE ÁGUA DE ALCÂNTARA (NOVA Lisboa)	Cachuco	2021	Thesis
Alcantara	Avaliação da evolução da vegetação nos telhados verdes da ETAR de Alcântara - contribuição para promover a conectividade ecológica em meio urbano. (Ulisboa)	Gomes	2022	Stage report
Alcantara	Otimização da linha de espessamento da ETAR de Alcântara (NOVA)	Santos	2018	Thesis

Algarve	ANÁLISE DE DESEMPENHO DE ESTAÇÕES DE TRATAMENTO DE ÁGUAS RESIDUAIS RECORRENDO A UM MODELO DE METABOLISMO (IST)	Rego	2012	Thesis
Alto Nabao	Avaliação da sensibilidade de gastrópodes a nitratos do efluente de uma ETAR (Instituto politecnico de Tomar)	Henriques	2015	Stage report
Alverca	Estude de impacto ambiental da etar de Alverca (SimTejo)		2002	Report
Ave	ESTUDO ENERGÉTICO COMPARATIVO DA ETAR DO AVE (UPorto)	Brandao	2018	Thesis
Ave	Análise da Viabilidade Económica da Reutilização de Águas Residuais Tratadas O caso da ETAR do Ave (Universidade do Minho)	Gomes	2011	Thesis
Barreiro-Moita	Eficiência de remoção de microplásticos em quatro ETAR portuguesas (FCT NOVA)	Gouveia	2018	Thesis
Beirolas	VALORIZAÇÃO AGRONÓMICA/ENERGÉTICA DE LAMAS DE ETAR: Estudo do Caso da ETAR de Beirolas	Bancessi	2009	Thesis
Camara de Lobos; Canico;Funchal; Machico; Ribeira Brava; Santa Cruz; Seixal	Projeto e Exploração de Estações de Tratamento de Águas Residuais (ETAR's) Metodologia de dimensionamento, sua definição e inventariação relativa às estruturas da RAM (Universidade da Madeira)	Machado	2016	Thesis
Carregado	Contributo para a otimização do desempenho da ETARI da Matutano no Carregado (Ulisboa)	Duarte	2017	Thesis
Castelo Branco	VALORIZAÇÃO DE LAMAS DE ETA NA ETAPA DE CONDICIONAMENTO DE LAMA DE ETAR (NOVA Lisboa)	Pires	2021	Thesis
Chelas; Beirolas; Frielas; Guia; Sao Joao da Talha; Vila Franca da Xira	Avaliação do desempenho da desidratação mecânica por centrifugação de lamas anaerobiamente digeridas: Caso de estudo de seis ETAR em Portugal (FCT NOVA)	Pinto	2019	Thesis
Choupal	Comparação da Modelação da Digestão Anaeróbia da ETAR do Choupal através de Redes Neuronais Artificiais e ADM1 (ESAC, Coimbra)	Amorim	2016	Thesis/stage report
Elvas	CONTRIBUIÇÃO PARA O TRATAMENTO E GESTÃO DAS LAMAS EM EXCESSO DAS ESTAÇÕES DE TRATAMENTO DE ÁGUAS RESIDUAIS – CASO DE ESTUDO DE OPTIMIZAÇÃO PARA 4 ETAR DO CONCELHO DE ELVAS (NOVA Lisboa)	Rasquilha	2010	Thesis
Espinho	Technical and economical assessment of the conversion of a conventional WWTP to reach energy neutrality and to provide water reclamation (NOVA)	Martins	2018	Thesis
Fatima	Avaliação de desempenho de ETAR urbanas (IPL, Leiria)	Jorge	2016	Thesis
Freixo	Avaliação do Efeito da Microfauna do Tanque de Arejamento no Efluente Final (ISEP, Porto)	Gomes	2013	Thesis

Frielas	Recuperação de estruvite à escala piloto na ETAR de Frielas (NOVA)	Bento	2023	Thesis
Gaia Litoral	Otimização etapa tratamento da de terciário da ETAR de Gaia Litoral (Universidade de Porto)	Figueiras	2020	Thesis
Gaia Litoral	Controlo e avaliação do sistema de tratamento de águas residuais da ETAR de Gaia Litoral e ETAR de Febros (UPorto)	Oliveira	2017	Thesis
Guia	ANÁLISE QUALITATIVA DE LAMAS DE ETAR E COMPETITIVIDADE ECONÓMICA DOS PROCESSOS DE TRATAMENTO E ESCOAMENTO: Caso da ETAR da Guia	Berco	2013	Thesis
Mangualde	Automatização da E.T.A.R. e Plano de Manutenção para a Adega Cooperativa de Mangualde (Instituto politecnico de Viseu)	Lopes	2015	Stage report
Mutela	Estudo de Melhoria de Gestão de Manutenção de uma Estação de Tratamento de Águas Residuais (N0VA)	Queiroz	2015	Thesis
Norte de Leiria-Coimbrao	Diagnóstico do desempenho operacional de Estações de Tratamento de Água Residual (ETAR) e avaliação do potencial de valorização agrícola do efluente tratado – Casos de estudo das ETAR de Montemor-o-Velho e da ETAR Norte de Leiria/Coimbrão (ESAC, Coimbra)	Santos	2018	Thesis
Palmeira	Estudo Técnico dos Problemas Operacionais da ETAR de Palmeira em Braga e Elaboração de Soluções de Melhoria (FEUP, Porto)	Carvalho	2016	Thesis
Palmela auto europa	Estudo da Eficiência da ETAR da Zona Industrial da AutoEuropa por Análise Biológica	Francisco	2008	Thesis
PInhal Novo	REABILITAÇÃO DE ETAR URBANA DE PEQUENA/MÉDIA DIMENSÃO CASO DE ESTUDO DA ETAR DO PINHAL NOVO (NOVA)	Fernandes	2021	Thesis
PInhal Novo	A Directiva ATEX 137 em Saneamento Básico (FEUP, Porto)	Dias	2008	Thesis
Ponte da Baia	Digestão Anaeróbia – Co-digestão de óleos, gorduras e lactosoro na ETAR do Sousa e ETAR de Ponte da Baia (Universidade de Porto)	Alves	2020	Stage report
Quinta da Bomba; Serzedelo	Energy and Carbon Balance in Wastewater Treatment Plants (IST)	Duarte	2024	Thesis
Quinta no conde	Eficiência de remoção de microplásticos em quatro ETAR portuguesas (FCT NOVA)	Gouveia	2018	Thesis
Rabada	Otimização da Amostragem e Estudo de Viabilidade da Monitorização de Sondas na ETAR de Rabada (ISEP, Porto)	Da Silva	2014	Thesis
Santa Cita	Eficiência energética no setor do tratamento de água residual. Caso de estudo: ETAR de Santa Cita	Ferreira	2018	Thesis
Sao Joao da Talha	Otimização do Tratamento Primário da ETAR de São João da Talha (FCT, NOVA)	Nabais	2018	Thesis

Simria Norte	CAPACIDADE DE NITRIFICAÇÃO E DESNITRIFICAÇÃO DA ETAR NORTE-SIMRIA (Universidade de Aveiro)	Ribeiro	2013	Thesis
Seixal	Aplicação de redes neuronais artificiais na gestão da produção de biogás resultante de processos de digestão anaeróbia	Reis	2015	Thesis
Setubal; Pedrogao Grande; Fatima	ANÁLISE COMPARATIVA DE SISTEMAS DE DESIDRATAÇÃO PARA ETAR CASO DE ESTUDO: CENTRÍFUGAS VERSUS FILTROS BANDA	Ramos	2011	Thesis
Simria Sul	Capacidade de nitrificação e desnitrificação da ETAR Sul da SIMRIA (Universidade de Aveiro)	Da Silva	2013	Thesis
Sobreiras	USO EFICIENTE DE ENERGIA E DE REAGENTES NA ETAR DE SOBREIRAS (FEUP, Porto)	Alvarado	2016	Thesis
Tolosa	Remoção da carga orgânica afluente à ETAR de Tolosa por coagulação-floculação química	Soares	2009	Thesis
Viseu Sul	Avaliação de risco de reutilização da água tratada da ETAR Viseu Sul para usos de rega e afins (Instituto politecnico de Viseu)	Santos	2023	Stage report

During chapter 5 analysis the originally empty uwwWasteWaterTreated column was partly filled.

COD, BOD, N and P discharge and incoming load columns, typically empty, were filled when possible.

Additional COD, BOD, N and P % removal and effluent concentrations columns were added, even if the web search allowed to fill them in just a very limited number of cases.

The dataset was then additionally expanded by adding columns referring to the main water line missing and present treatment steps. A more detailed clarification of the water line treatment steps was done by adding multiple columns towards the end of the sheet.

Performance columns related to sludge production, land, chemicals, and energy consumption were added too.

Many of the performances columns entries remained empty even after the web search.

All added columns headings are highlighted in grey to make them distinguishable, as all entries in any column that were originally empty and where then filled through the web source.

Chapter 6 started with a selection of reference Danish WWTPs. From the original November 2025 downloaded CSV file Danish WWTPs in UWWTPS sheet were selected through choosing “DK” in “rptMStateKey_perfData”. Danish WWTPs with design capacity below 10 000 pe were immediately excluded.

Subsequently, thanks to the available values for uwwWasteWaterTreated column and COD, BOD, N, and P incoming and discharge loads, columns COD, BOD, N, P % removal and effluent concentrations were computed and added through 8 columns to the dataset, without the need of any web search, just using data already available from EU dataset.

Then WWTPs with N and P % removals respectively above 85% and 90% and N and P effluent concentrations respectively below 8 mg/L and 0,7 mg/L were filtered out to form the list of reference WWTPs.

The reason behind the choice to require minimum 85% and 90% N and P removal instead of the 80 and 87,5 as table Table 2-2 expects is to shorten the list of possible reference WWTPs to make the following water line web search more compact.

In the end the list was formed by 127 WWTPs.

Columns uwwNUTS, uwwCode, uwwName, uwwCapacity, uwwWasteWaterTreated, together with computed columns N% removal, N effluent, P % removal and P effluent were extracted for the 127 rows corresponding to the reference list WWTPs to form the base dataset for chapter 6.

A web search to find the water line nutrients removal sequences of each one of these WWTPs was conducted. The uwwNUTS, uwwCode and uwwName columns entries where typed on the web together with “renseanlæg”, “WWTP”, “thesis”, “online control”, “SCADA” and “scheme” key words. Only in 47 cases the search was successful.

Prioritized sources where: DinGeo site, Municipalities Wastewater official pages and thesis dissertations. Through the web search the reference Danish WWTP dataset was enlarged adding columns for the water line treatment steps and strategies adopted, performances and extra sources, as already done for chapter 5 with the to retrofit-Portuguese list dataset.

In Table 1-7 a list of the thesis and reports mainly used to derive Danish reference WWTPs characterization is given. The totality of the external sources, compreehensive of indexed papers and municipalities web pages is given in the excel spreadsheet.

Table 1-7: Documents used for reference Danish WWTPs characterization

WWTP	TITLE (COMPANY)	AUTHOR	YEAR	TYPE OF DOCUMENT
Aalborg Øst	Analysis of Aalborg East Waste Water Treatment Plant (Aalborg University)		2008	GROUP PROJECT
Aalborg Øst	Application of nitritation and denitritation process in treatment of cattle slaughterhouse wastewater. (Aalborg University)	Marcinkowski	2004	THESIS
Aalborg Vest	Identification of wastewater processes (IMSOR)	Carstensen	1996	PhD THESIS
Spildevandscenter Avedøre	Implementation of a dynamic cost calculation module for Avedøre WWTP using WEST (Université Laval)	Mathieu Beaupré, Leiv Rieger ,Peter A. Vanrolleghem, Ulf Jeppsson	2008	PROJECT REPORT
Spildevandscenter Avedøre	Phosphorus recycling in urban areas. A comparative study of nutrient recycling from urban wastewater in two Danish cities. (Roskilde University)	Eromosele Courage Imonitie	2016	PRE-THESIS

Bjergmarken	Phosphorus recycling in urban areas. A comparative study of nutrient recycling from urban wastewater in two Danish cities. (Roskilde University)	Eromosele Courage Imonitie	2016	PRE-THESIS
Egå	EUDP Final Report: Energy Generation from Waste Water Plants		2018	REPORT
Ejby Mølle Renseanlæg	Bilag 2 - Chemical phosphorus (P) mapping in wastewater treatment plants (WWTPs) towards efficient P recovery (University of Southern Denmark)	Qian Wang and Ulla Gro Nielsen	2022	PROJECT REPORT
Esbjerg vest	Efficiency of selective hydrolysis on anaerobic mineralisation of WWTP sludge, Esbjerg West waste water treatment plant, Denmark	Niels Østergaard, Flemming Andersen	2015	REPORT
Esbjerg vest	Bilag 2 - Chemical phosphorus (P) mapping in wastewater treatment plants (WWTPs) towards efficient P recovery (University of Southern Denmark)	Qian Wang and Ulla Gro Nielsen	2022	PROJECT REPORT
Fårevejle renseanlæg	Ressourcetjek af udvalgte renseanlæg Partnerskab om ressourceudnyttelse i vandsektoren (NIRAS, Vadcenter Syd)	Lars-Christian Sørensen, Per Henrik Nielsen, Ib Pedersen	2020	REPORT
FREDERICIA SPILDEVAND OG ENERGI A/S	Bilag 2 - Chemical phosphorus (P) mapping in wastewater treatment plants (WWTPs) towards efficient P recovery (University of Southern Denmark)	Qian Wang and Ulla Gro Nielsen	2022	PROJECT REPORT
Frederikshavn	WWTP Process Tank Modelling The Integration of Advanced Hydrodynamicand Microbiological Model (Aalborg University)	Laursen	2007	THESIS
Grindsted	Bilag 2 - Chemical phosphorus (P) mapping in wastewater treatment plants (WWTPs) towards efficient P recovery (University of Southern Denmark)	Qian Wang and Ulla Gro Nielsen	2022	PROJECT REPORT
Grindsted	BILLUND BIOREFINERY – ADVANCING THE RECYCLE CIRCLE (Veolia UK)	Gilbert	2016	PROJECT REPORT
HOLBÆK	Greenhouse gas emissions from wastewater treatment plants: measurements and carbon footprint assessment (DTU)	Delre	2018	PhD THESIS
Holstebro	Ressourcetjek af udvalgte renseanlæg Partnerskab om ressourceudnyttelse i vandsektoren (NIRAS, Vadcenter Syd)	Lars-Christian Sørensen, Per Henrik Nielsen, Ib Pedersen	2020	REPORT
KOLDING CENTRALRENS.	Modeling and Optimization of Wastewater Treatment Plants with Deep Learning and Reinforcement Learning (Aalborg University)	Mohammadi	2025	PhD THESIS
Marselisborg	The Energy Positive WWTP Wastewater as a major challenge and a great opportunity (Aarhus vand)	Flemming B. Moller	2018	CONFERENCE REPORT
Nivå Renseanlæg	Ressourcetjek af udvalgte renseanlæg Partnerskab om ressourceudnyttelse i vandsektoren (NIRAS, Vadcenter Syd)	Lars-Christian Sørensen, Per Henrik Nielsen, Ib Pedersen	2020	REPORT
Skanderborg Centralrenseanlæg	Data-driven Modeling and Predictive Control for N2O Mitigation in Wastewater Treatment Processes (Aalborg University)	Hansen	2025	PhD THESIS

SLAGELSE	Ressourcetjek af udvalgte renseanlæg Partnerskab om ressourceudnyttelse i vandsektoren (NIRAS, Vadcenter Syd)	Lars-Christian Sørensen, Per Henrik Nielsen, Ib Pedersen	2020	REPORT
Tarm	Ringkøbing-Skjern Kommune Bilag 7 til Spildevandsplan 2024-2031 RENSEANLÆG		2025	REPORT

Chapter 7 and 8 were entirely built from web and literature research.

2 Appendix – Danish WWTPs reference list

List of the Danish plants above 10 000 pe design capacity achieving more than 90% N removal, more than 85% P removal, less than 8 mg/L N in effluent and less than 0,7 mg/L of P in effluent

Datahub (EEA)

Table 2.1: List of possible Reference Danish wwtps

List of possible Reference Danish wwtps		
uwwNUTS	uwwCode	uwwName
DK013	DK1510001	Måløv Rens
DK011	DK1550001	Dragør
DK013	DK2010005	Lillerød Renseanlæg
DK013	DK2050001	Sjælsø
DK013	DK2070002	Stavnsholt
DK013	DK2090004	Frederikssund
DK014	DK2190020	HCRSyd
DK013	DK2230002	Usserød
DK013	DK2250019	Tørslev
DK013	DK2270005	Nivå Renseanlæg
DK013	DK2330005	Slangerup
DK013	DK2350006	Stenløse
DK013	DK2370010	Ølstykke
DK022	DK2530001	Mosede
DK013	DK2550001	Jyllinge
DK022	DK2570001	Hvalsø
DK022	DK2590009	Køge-Egnens Renseanlæg I/S
DK022	DK2630001	Viby
DK022	DK2650002	Bjergmarken
DK022	DK2690001	Solrød
DK022	DK2710016	Strøby Ladeplads
DK022	DK3050006	Fårevejle renseanlæg
DK022	DK3130005	HASLEV C.
DK022	DK3250012	KORSØR RENSEANLÆG

DK022	DK3290030	RINGSTED C
DK022	DK3310010	SKÆLSKØR
DK022	DK3330007	SLAGELSE
DK022	DK3350012	SORØ CENTRALRENSEANLÆG
DK022	DK3410011	TORNVED C.
DK022	DK3510001	FAKSE
DK022	DK3570004	HOLME OLSTRUP
DK022	DK3650006	STEGE
DK022	DK3690001	NYKØBING F. NORD
DK022	DK3770011	Præstø Renseanlæg
DK022	DK3830004	RØDBY HAVN
DK022	DK3890001	U8 ST.HEDDINGE
DK022	DK3950001	Marielyst Renseanlæg
DK014	DK4070101	Rønne Renseanlæg
DK031	DK4211102	Assens Renseanlæg
DK031	DK4271102	Egebjerg syd Renseanlæg
DK031	DK4351402	Strandgården Renseanlæg
DK031	DK4391202	Kerteminde/Munkebo
DK031	DK4510102	Nr. Åby Renseanlæg
DK031	DK4610102	Nordvest Renseanlæg
DK031	DK4610202	Nordøst Renseanlæg
DK031	DK4710102	Otterup Renseanlæg
DK031	DK4735102	Ringe Renseanlæg
DK031	DK4751202	Rudkøbing Renseanlæg
DK031	DK4791302	Egsmade Renseanlæg
DK031	DK4830102	Søndersø By Renseanlæg
DK031	DK4950102	Ørbæk Renseanlæg
DK032	DK5090006	CHRISTIANSFELD RENSEANLÆG
DK032	DK5150001	HADERSLEV
DK032	DK5230004	HIMMARK
DK032	DK5390001	Gårdeby Renseanlæg
DK032	DK5410007	TØNDER
DK032	DK5430001	VOJENS
DK032	DK5530002	Outrup Renseanlæg
DK032	DK5590001	Brørup
DK032	DK5610001	Esbjerg vest
DK032	DK5610002	Esbjerg øst
DK032	DK5650012	Grindsted
DK032	DK5690001	Holsted by
DK032	DK5710001	Ribe
DK032	DK5750001	Vejen
DK032	DK5770010	Skovlund Renseanlæg
DK042	DK6010029	Brædstrup

DK042	DK6030020	BREJNING CENTRALRENS.
DK042	DK6050100	HARALDSKÆR RENSEANLÆG
DK042	DK6070012	FREDERICIA SPILDEVAND OG ENERGI A/S
DK041	DK6110004	GIVE CENTRALRENS.
DK042	DK6130041	Hedensted Renseanlæg
DK042	DK6190001	Juelsminde
DK032	DK6290003	VAMDRUP RENSEANLÆG
DK041	DK6551002	Tarm
DK041	DK6571002	Herning - HCR
DK041	DK6591002	Hvide Sande
DK041	DK6611002	Holstebro
DK041	DK6631002	Ikast
DK041	DK6651002	Lemvig
DK041	DK6711002	Struer
DK041	DK6731202	Harboøre
DK041	DK6811002	Videbæk
DK041	DK6831002	Vinderup
DK042	DK7010033	Boeslum
DK042	DK7030027	Skovby Renseanlæg
DK042	DK7050014	Truust CR
DK042	DK7090005	Hadsten
DK042	DK7110003	Hammel
DK042	DK7130003	Hinnerup
DK042	DK7150039	Hørning Renseanlæg
DK042	DK7170004	Langå
DK042	DK7270071	Odder. Saksild Bugt
DK042	DK7330009	Mørke
DK042	DK7370001	Ry Renseanlæg
DK042	DK7430001	Søholt
DK042	DK7450024	Skanderborg Centralrenseanlæg
DK042	DK7490011	Them
DK042	DK7510186	Egå
DK042	DK7610202	Bjerringbro
DK050	DK7650302	Hanstholm Renseanlæg
DK041	DK7690202	Karup
DK041	DK7710202	Kjellerup
DK050	DK7730678	Østerstrand
DK041	DK7790202	Skive
DK050	DK7850202	Tåbel
DK050	DK7870002	Thisted
DK050	DK8030009	Attrup
DK050	DK8090362	Stistrup
DK050	DK8190545	Hirtshals

DK050	DK8210138	Hjørring
DK050	DK8290389	Nr. Lyngby
DK050	DK8400001	Mariagerfjord Renseanlæg
DK050	DK8410526	Skagen
DK050	DK8510144	Aalborg Øst
DK050	DK8610051	Aars Renseanlæg

Table 2.1 continued: List of possible Reference Danish wwtps

List of Reference Danish wwtps		
uwwNUTS	uwwCode	uwwName
DK022	DK3730001	NÆSTVED
DK011	DK1010005	Renseanlæg Lynetten
DK011	DK1010006	Renseanlæg Damhusåen
DK012	DK1670001	Spildevandscenter Avedøre
DK031	DK4610302	Ejby Mølle Renseanlæg
DK050	DK8130337	Frederikshavn
DK050	DK8510333	Aalborg Vest
DK041	DK6671002	Ringkøbing
DK032	DK6210038	KOLDING CENTRALRENS.
DK042	DK7510138	Marselisborg
DK022	DK3150008	HOLBÆK

3 Appendix - Danish sub-groups of reference WWTPs schemes of treatment

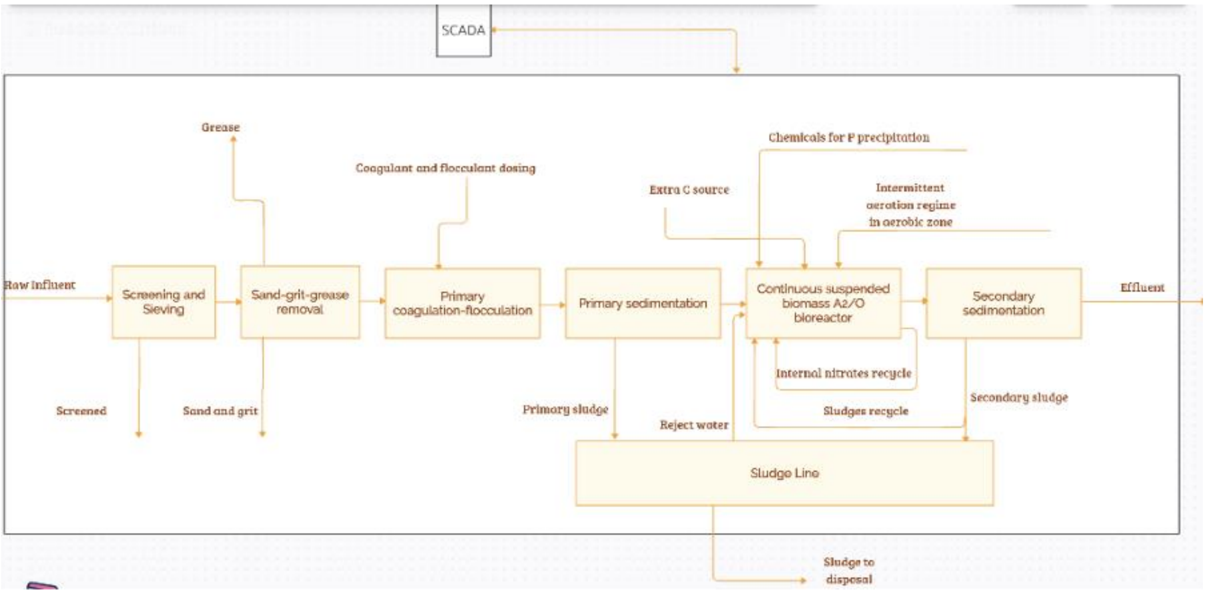

Figure 3.1: Block diagram representative of the water line of group 1 of reference Danish WWTPs

WWTPs of group 1: Lynetten

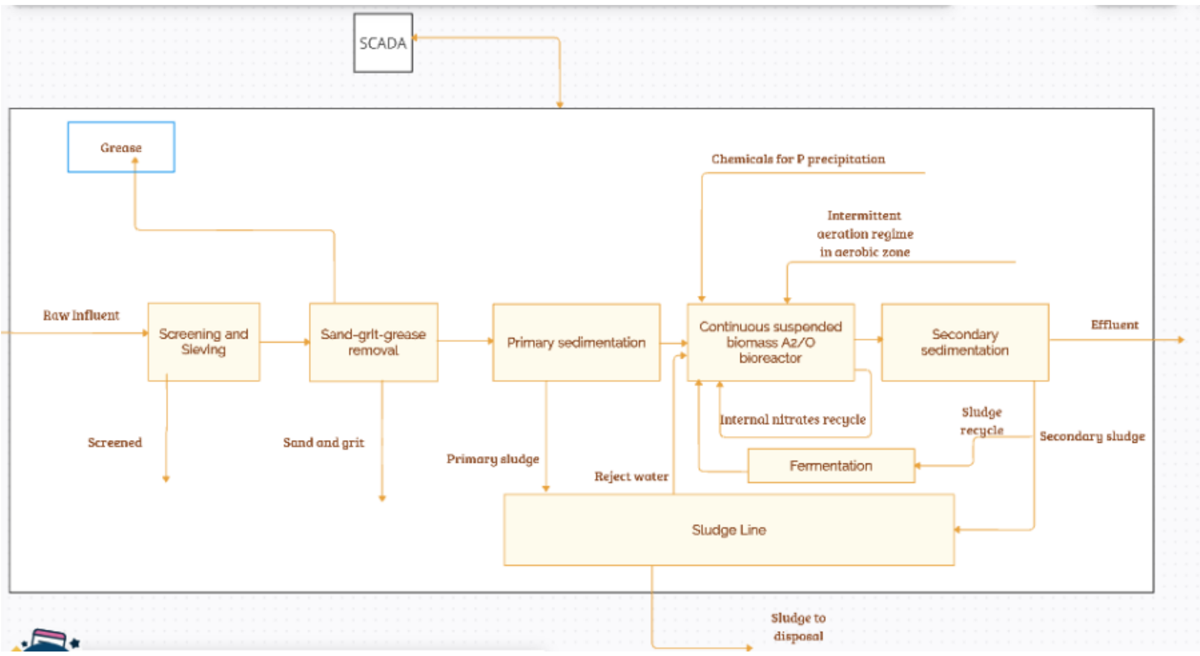

Figure 3.2: Block diagram representative of the water line of group 2 of reference Danish WWTPs

WWTPs of group 2: Avedore

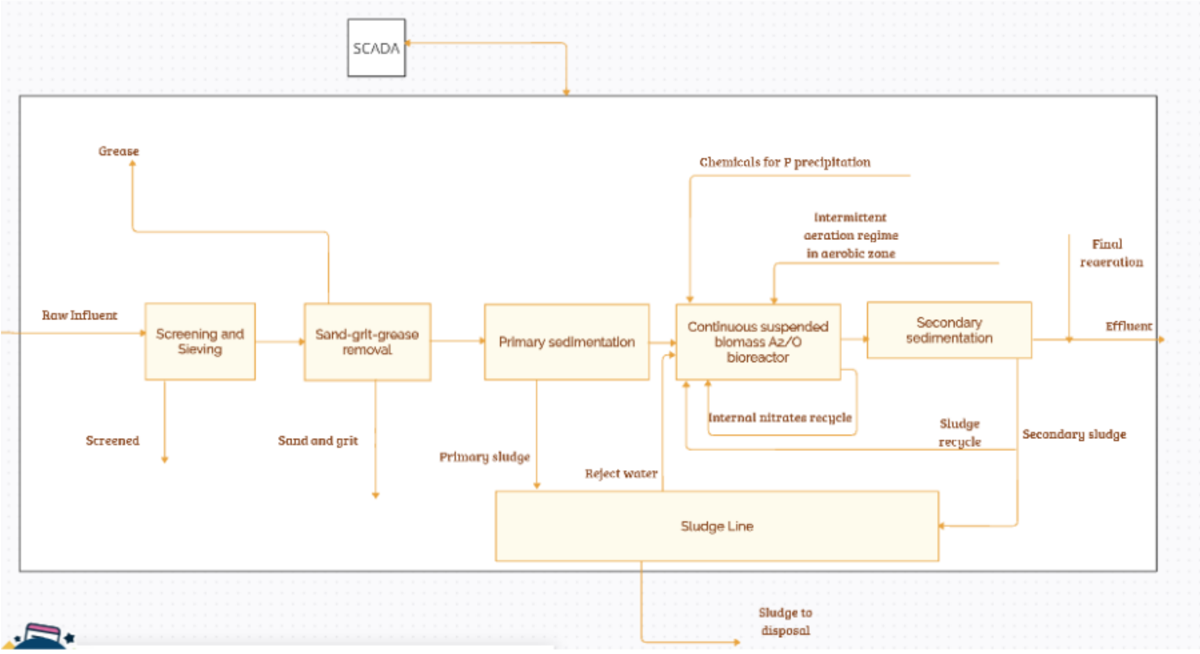

Figure 3.3: Block diagram representative of the water line of group 3 of reference Danish WWTPs

WWTPs of group 3: Niva

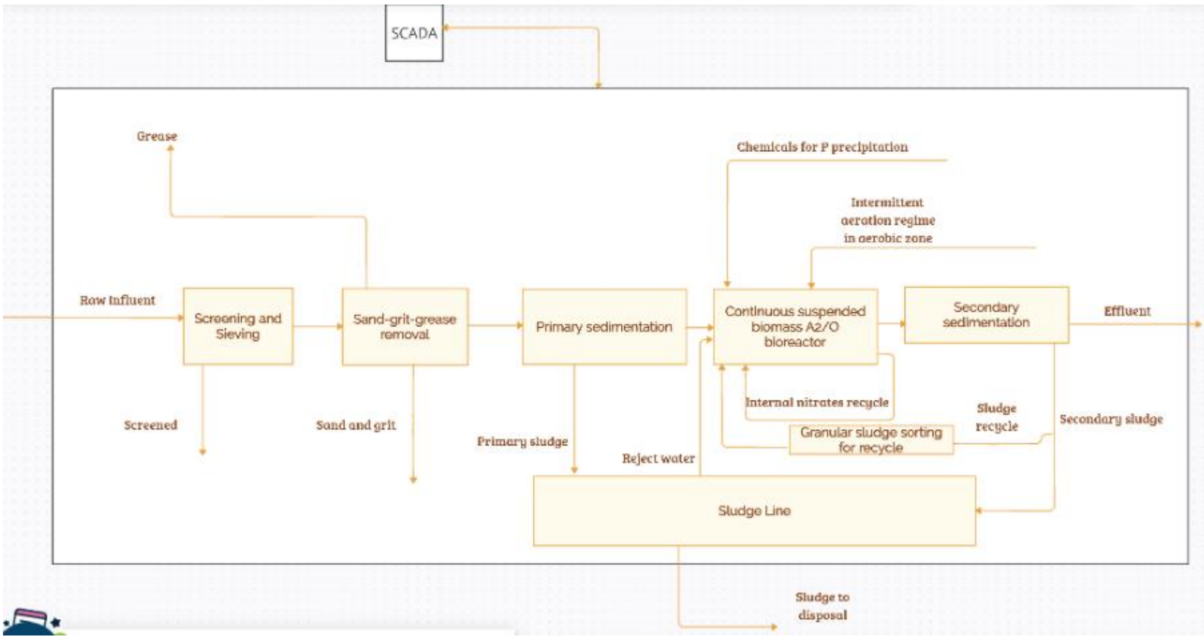

Figure 3.4: Block diagram representative of the water line of group 4 of reference Danish WWTPs

WWTPs of group 4: Aalborg west

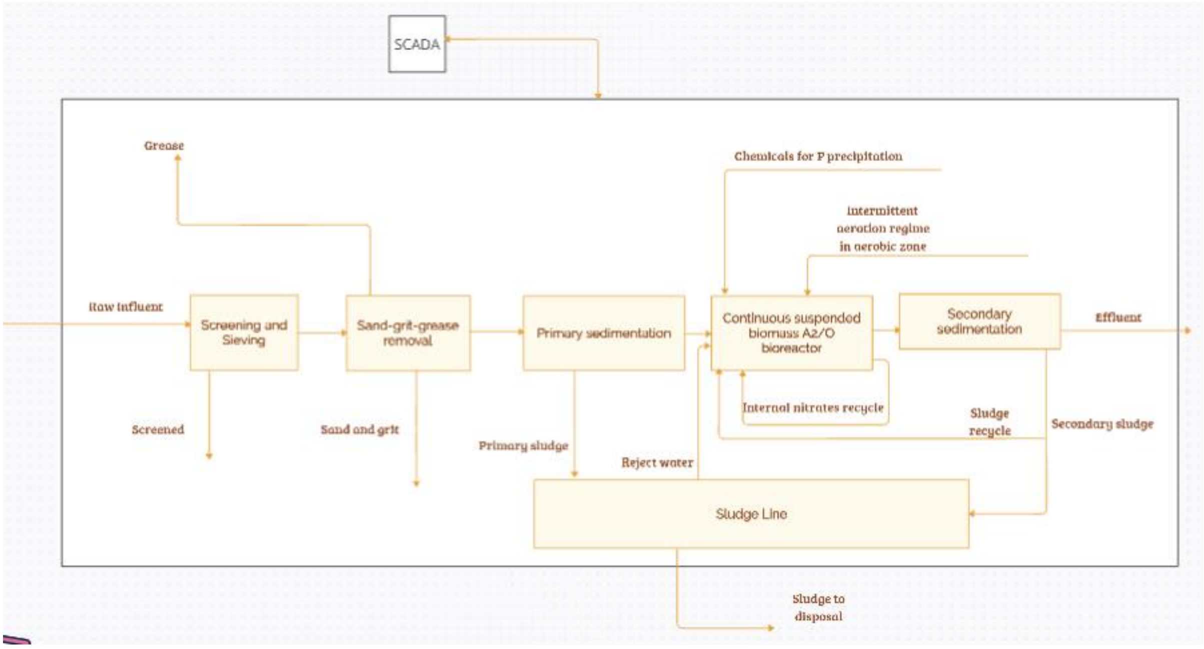

Figure 3.5: Block diagram representative of the water line of group 5 of reference Danish WWTPs

WWTPs of group 5: Skagen

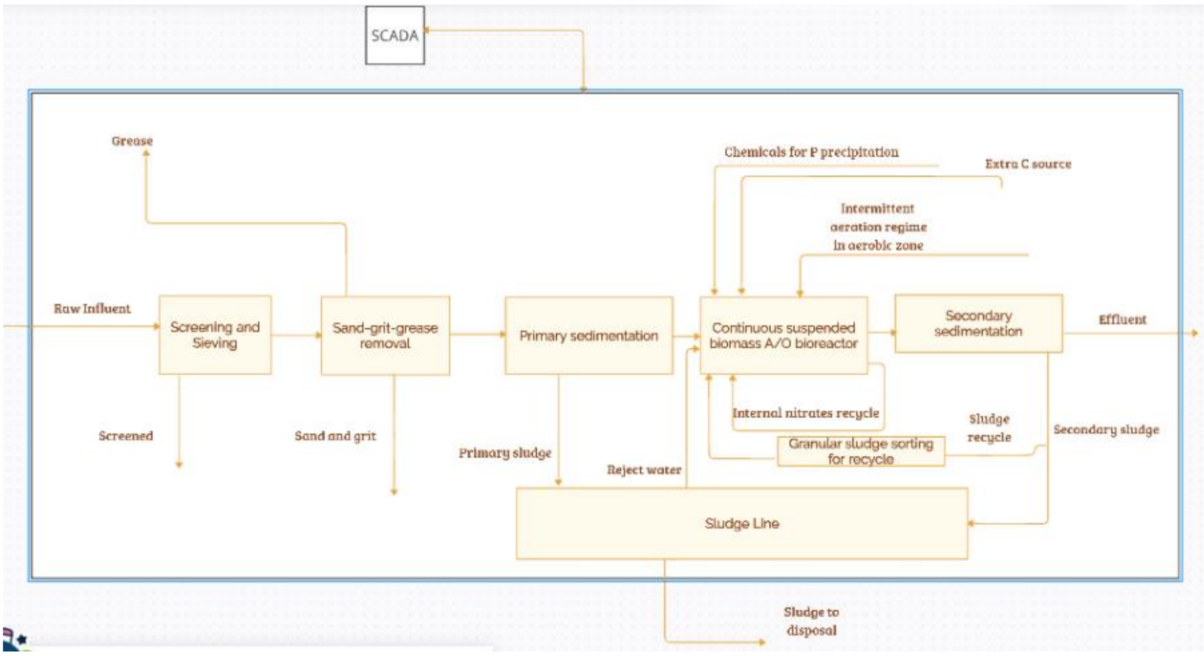

Figure 3.6: Block diagram representative of the water line of group 6 of reference Danish WWTPs

WWTPs of group 6: Viby

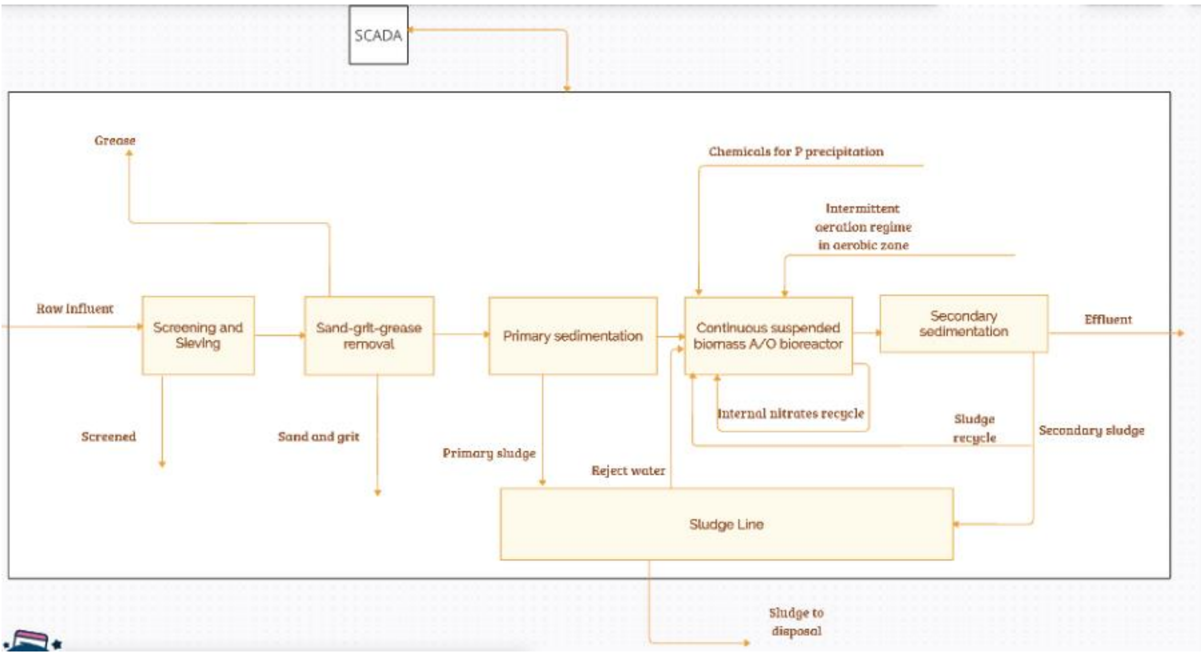

Figure 3.7: Block diagram representative of the water line of group 7 of reference Danish WWTPs

WWTPs of group 7: Korsor

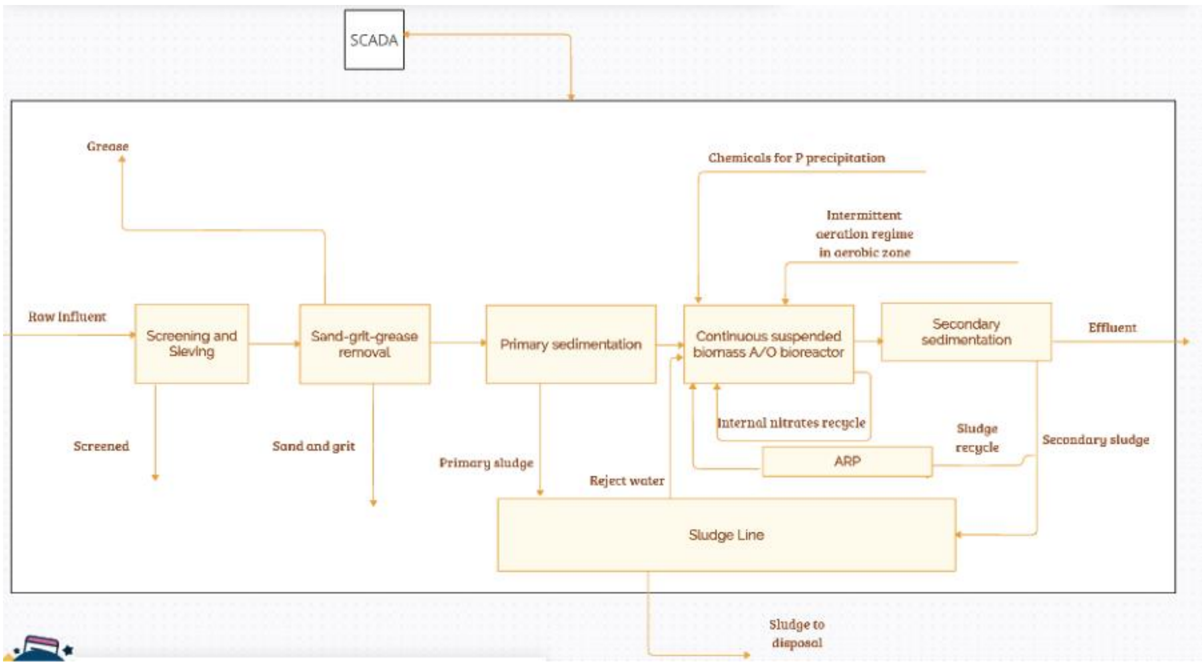

Figure 3.8: Block diagram representative of the water line of group 8 of reference Danish WWTPs

WWTPs of group 8: Slagelse

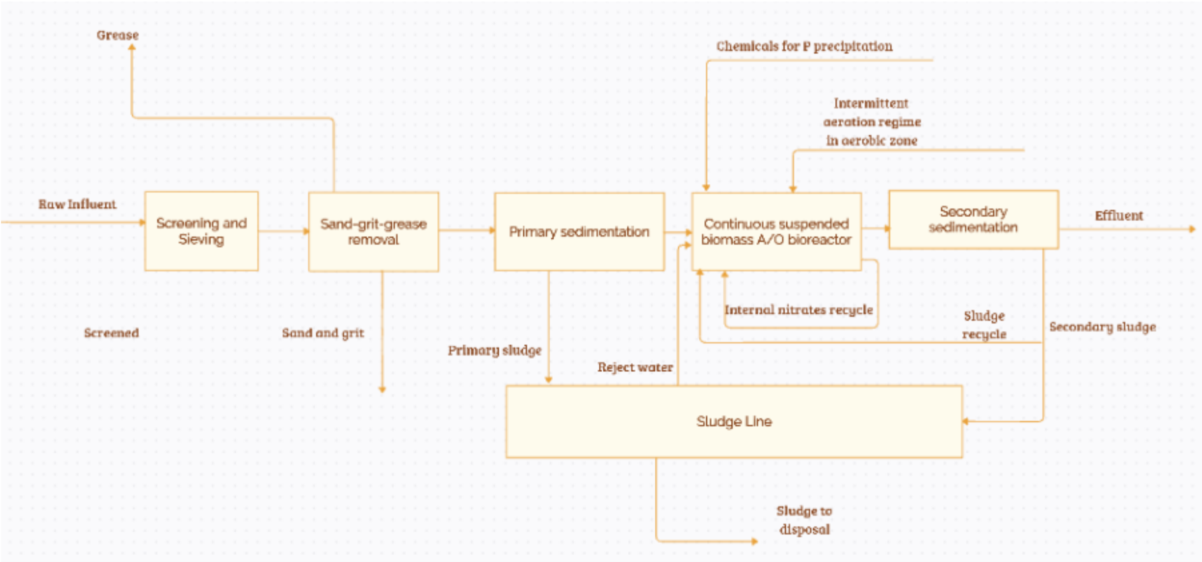

Figure 3.9: Block diagram representative of the water line of group 9 of reference Danish WWTPs

WWTPs of group 9: Ringkobing; Nr. Aby;
Northwest; Northeast; Otterup; Ringe; Christiansfeld; Haderslev; Himmark; Tarm

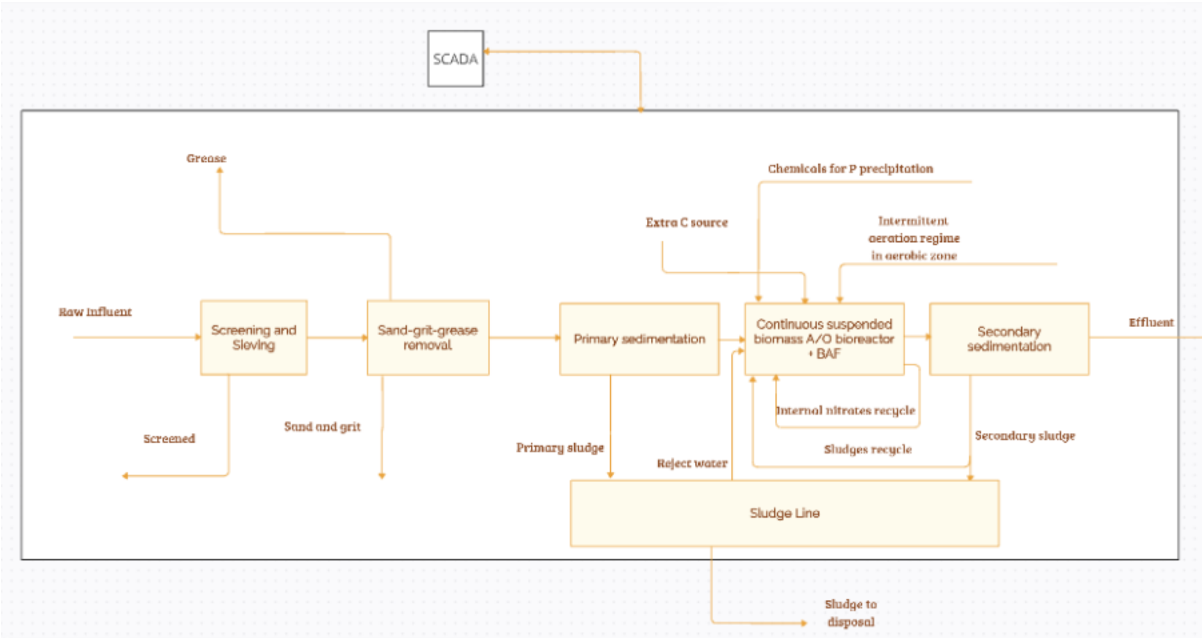

Figure 3.10: Block diagram representative of the water line of group 10 of reference Danish WWTPs

WWTPs of group 10: Frederikshavn

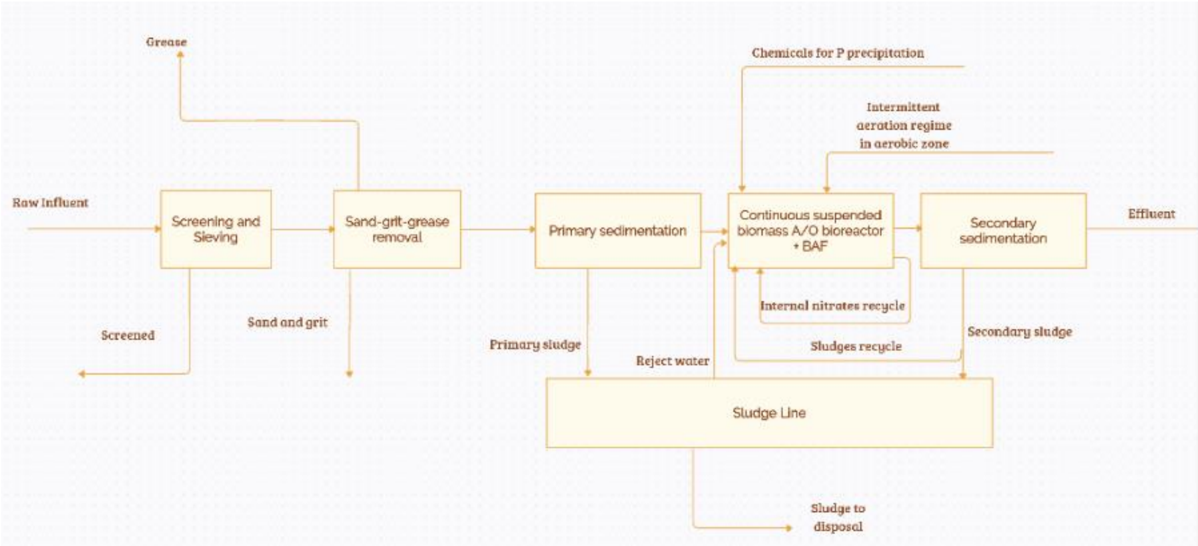

Figure 3.11: Block diagram representative of the water line of group 11 of reference Danish WWTPs

WWTPs of group 11: Stavnsholt

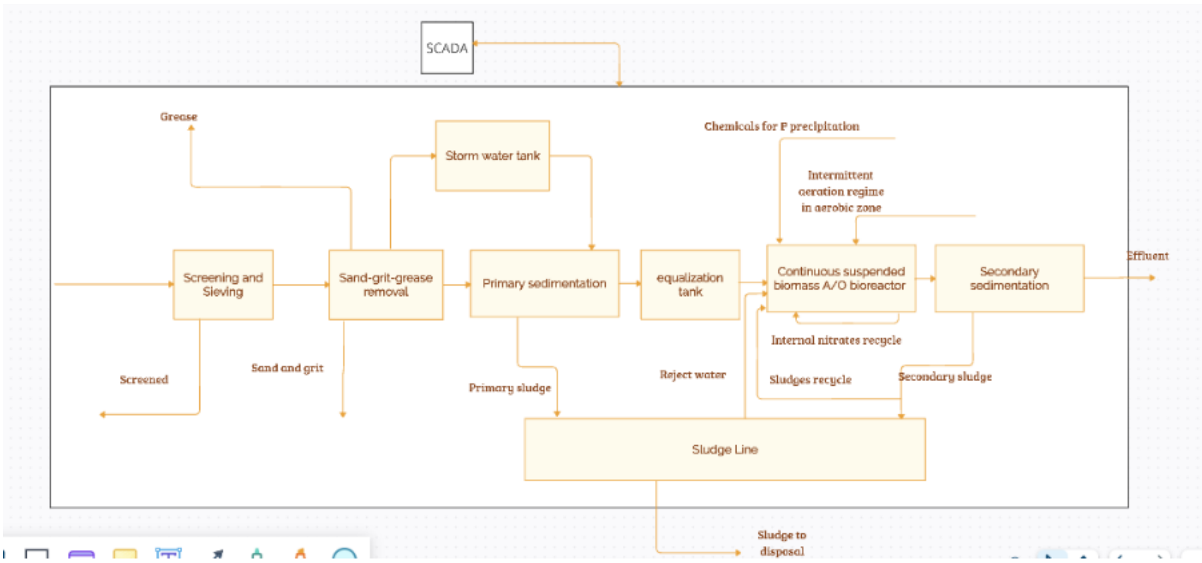

Figure 3.12: Block diagram representative of the water line of group 12 of reference Danish WWTPs

WWTPs of group 12: Koge-Egnens

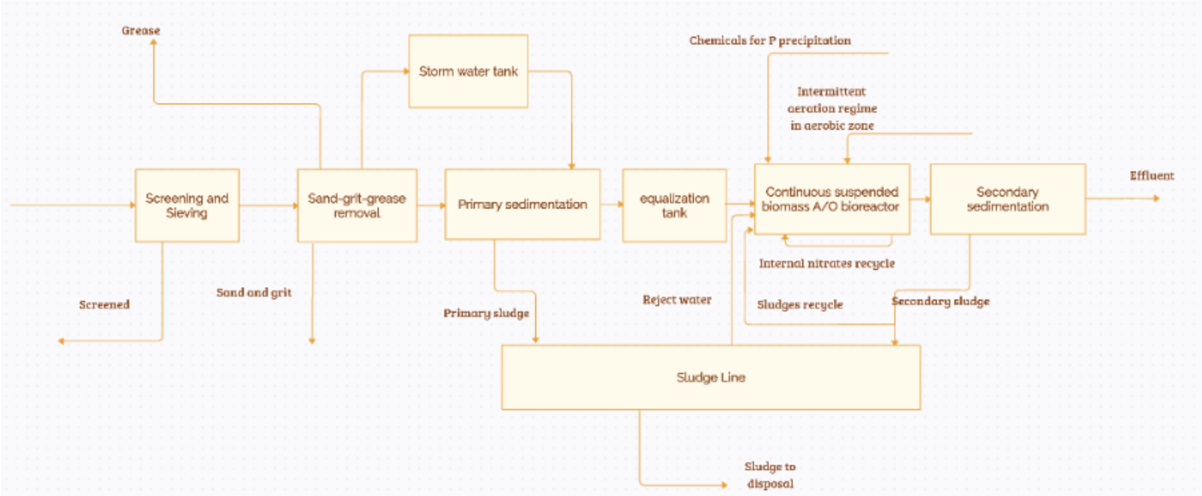

Figure 3.13: Block diagram representative of the water line of group 13 of reference Danish WWTPs

WWTPs of group 13: Esbjerg west

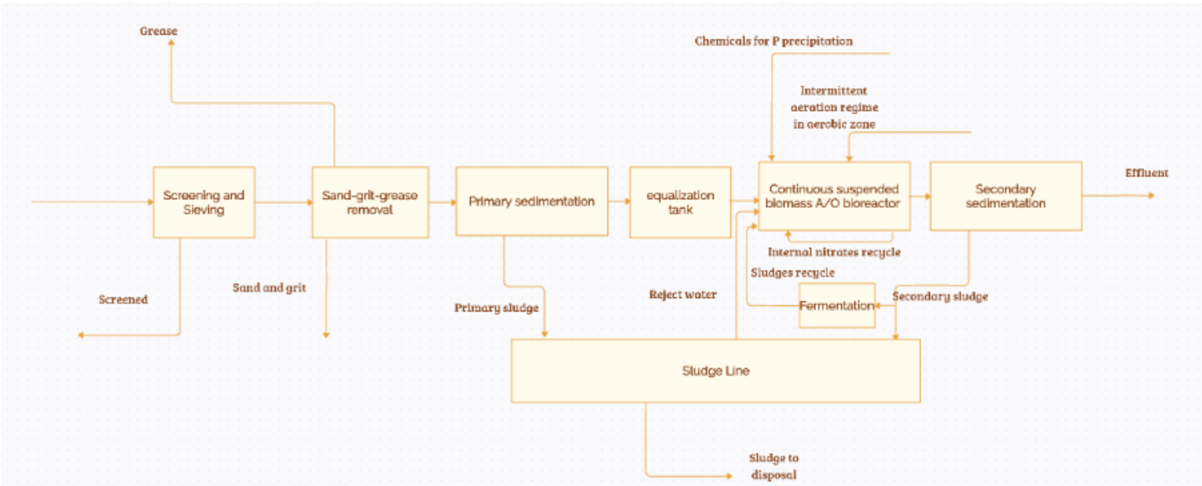

Figure 3.14: Block diagram representative of the water line of group 14 of reference Danish WWTPs

WWTPs of group 14: Damhusaen

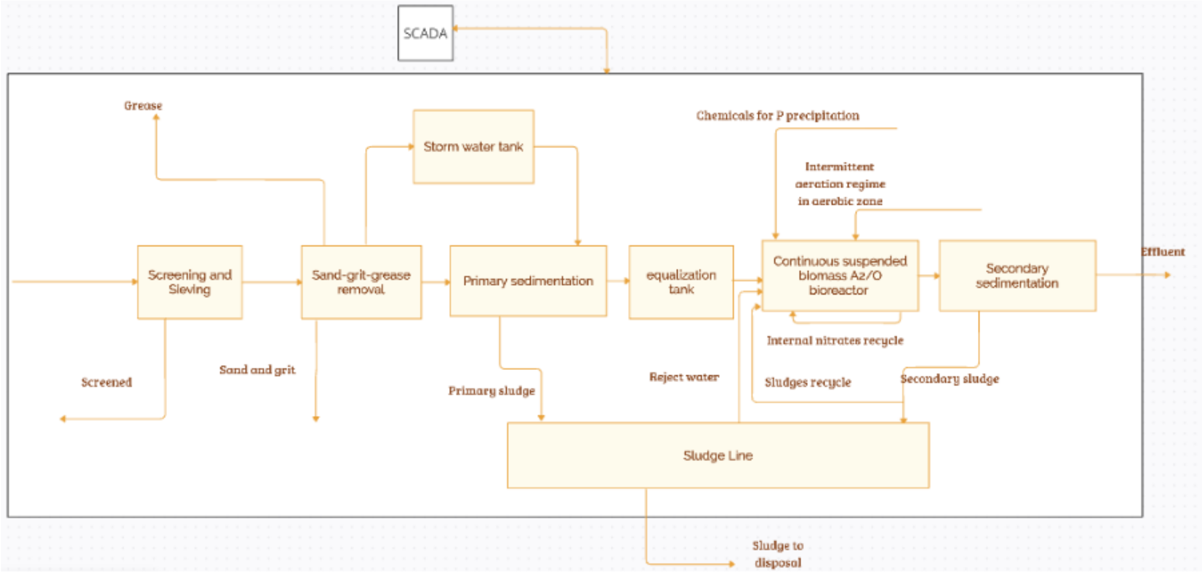

Figure 3.15: Block diagram representative of the water line of group 15 of reference Danish WWTPs

WWTPs of group 15: Kolding Central

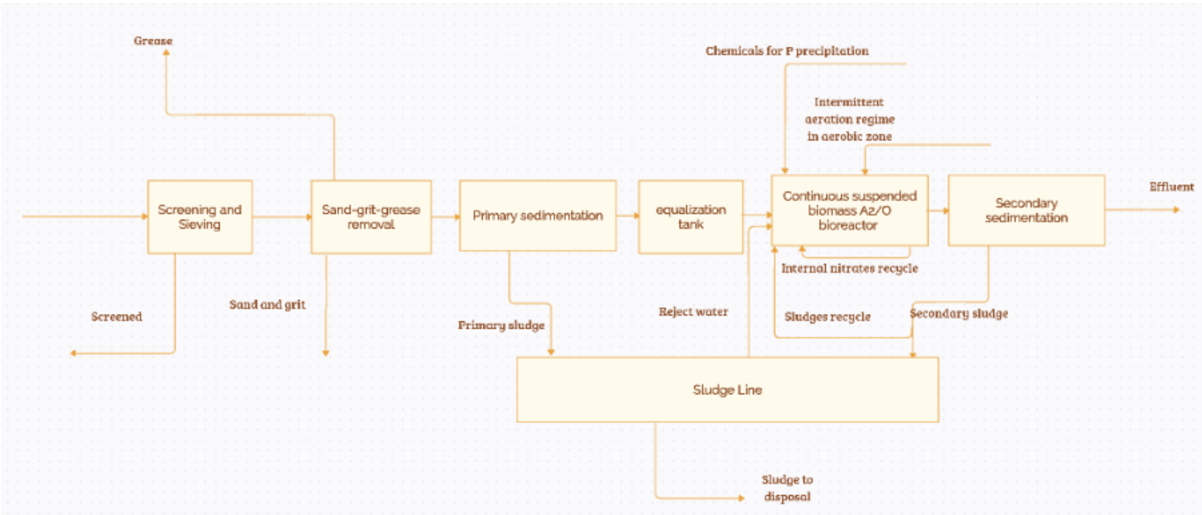

Figure 3.16: Block diagram representative of the water line of group 16 of reference Danish WWTPs

WWTPs of group 16: Mariagerfjord

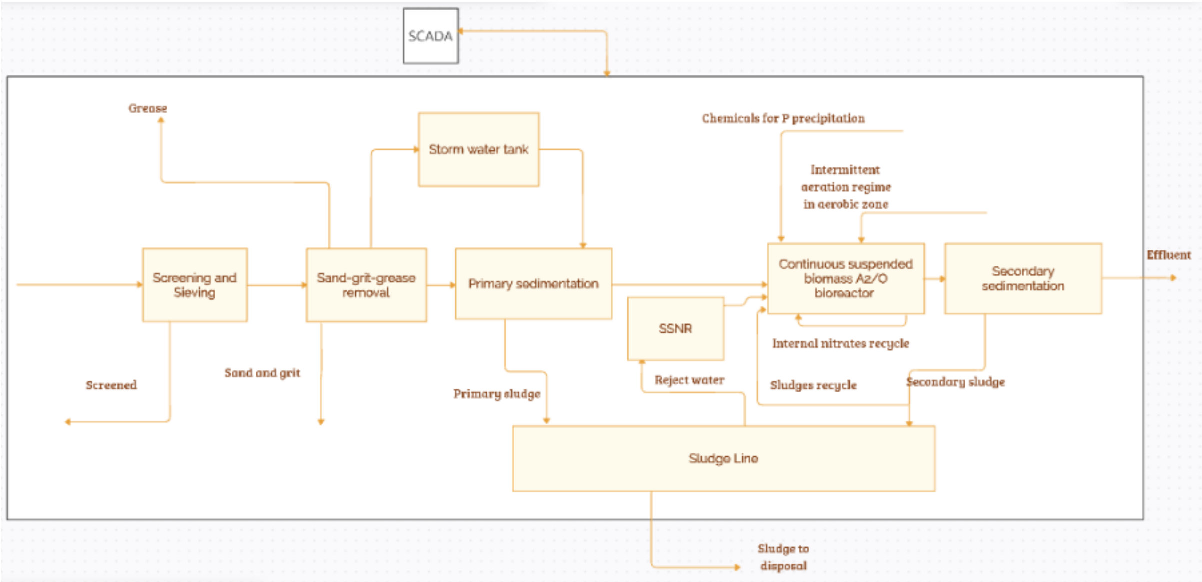

Figure 3.17: Block diagram representative of the water line of group 17 of reference Danish WWTPs

WWTPs of group 17: Marselisborg

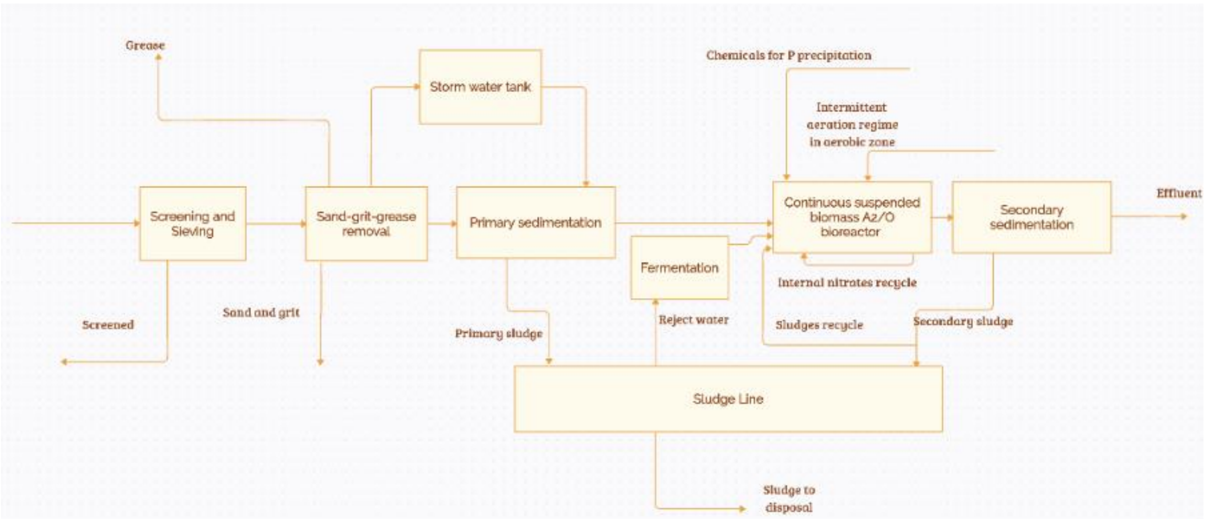

Figure 3.18: Block diagram representative of the water line of group 18 of reference Danish WWTPs

WWTPs of group 18: Aalborg East

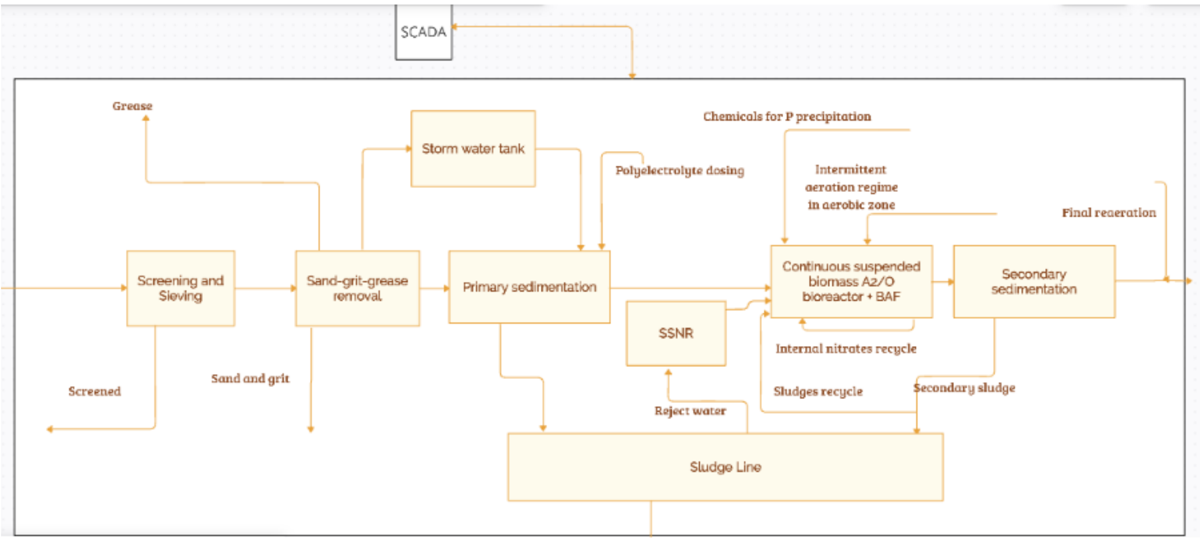

Figure 3.19: Block diagram representative of the water line of group 19 of reference Danish WWTPs

WWTPs of group 19: Ejby Molle

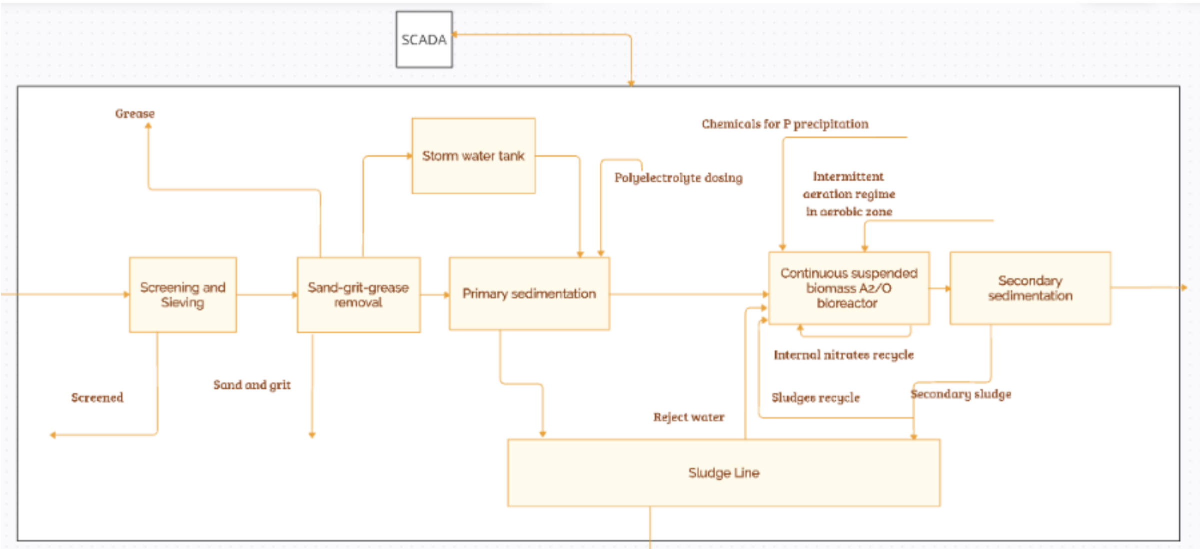

Figure 3.20: Block diagram representative of the water line of group 20 of reference Danish WWTPs

WWTPs of group 20: Fredericia

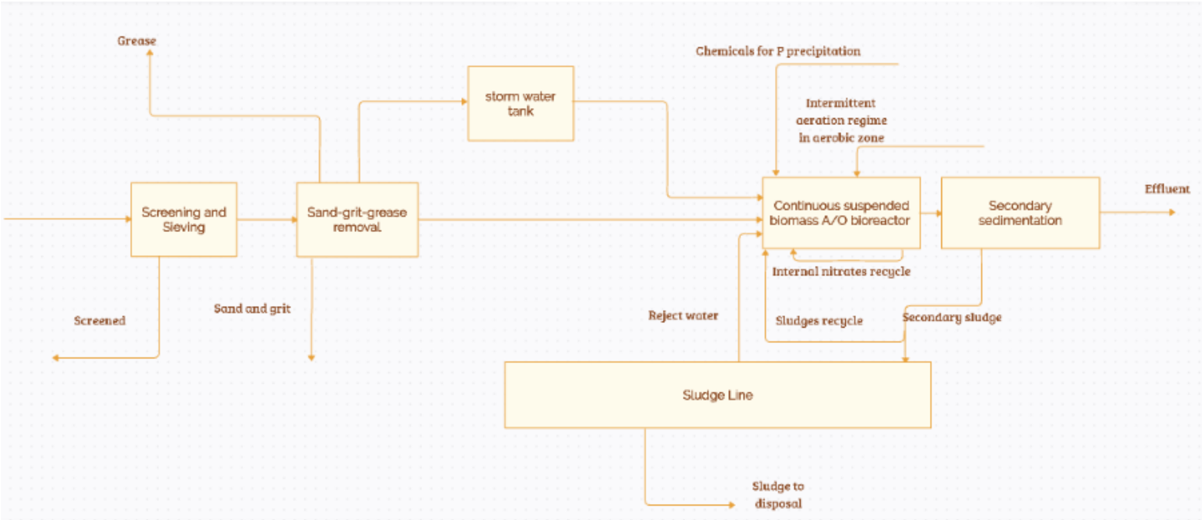

Figure 3.21: Block diagram representative of the water line of group 21 of reference Danish WWTPs

WWTPs of group 21: Lillerod

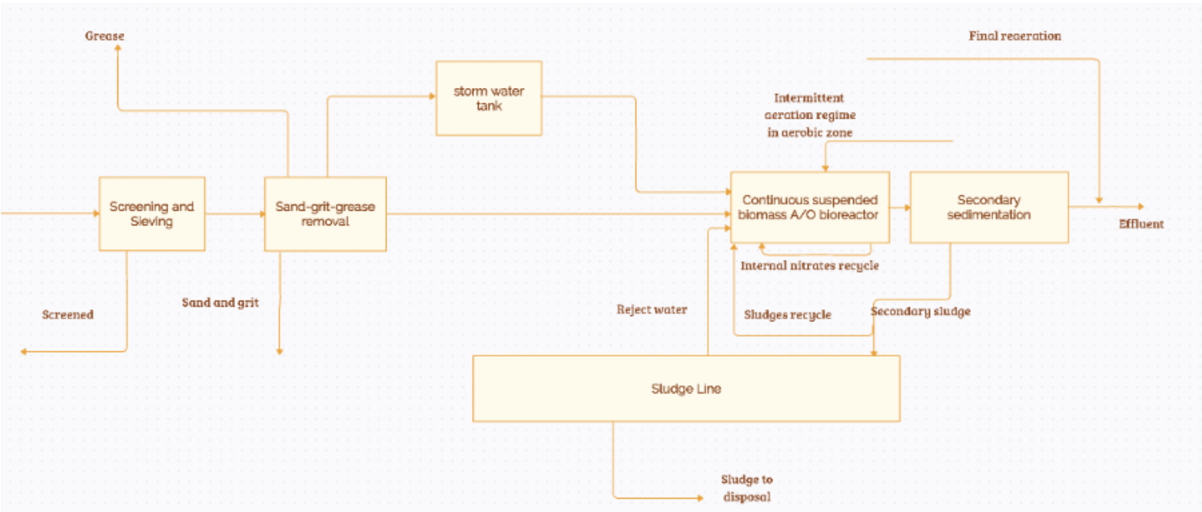

Figure 3.22: Block diagram representative of the water line of group 22 of reference Danish WWTPs

WWTPs of group 22: Naestved

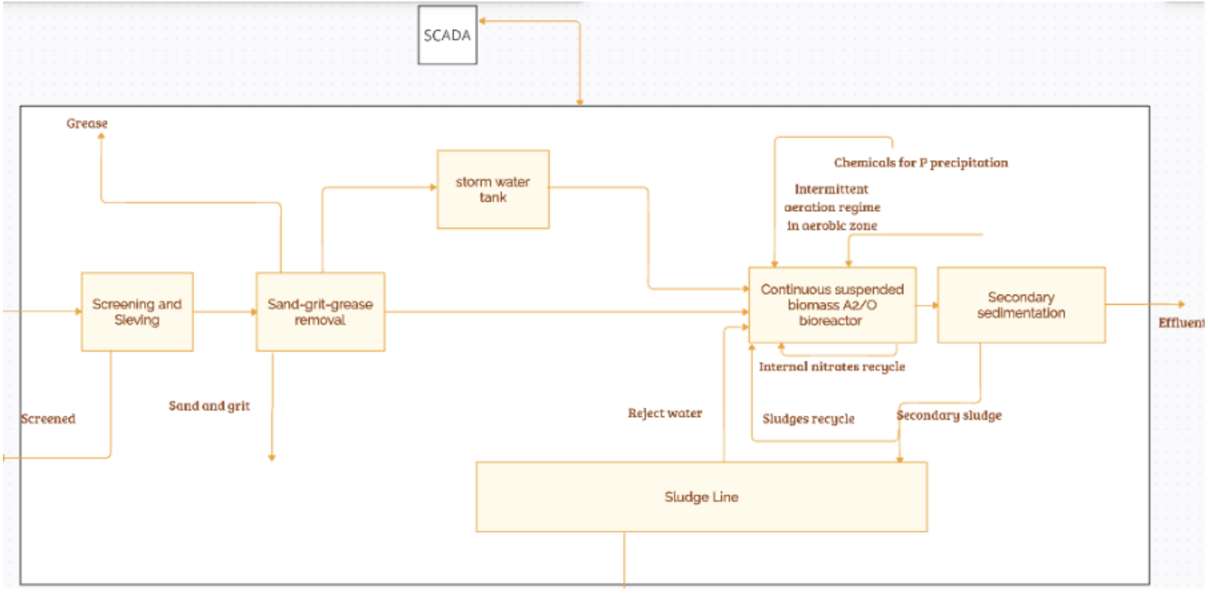

Figure 3.23: Block diagram representative of the water line of group 23 of reference Danish WWTPs

WWTPs of group 23: Skanderborg

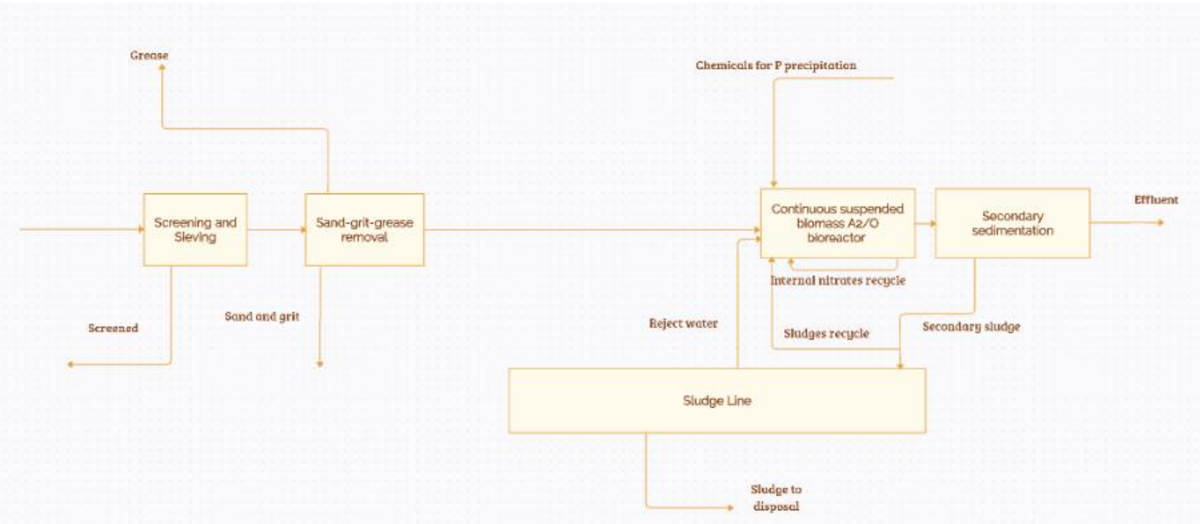

Figure 3.24: Block diagram representative of the water line of group 24 of reference Danish WWTPs

WWTPs of group 24: Bjergmarken

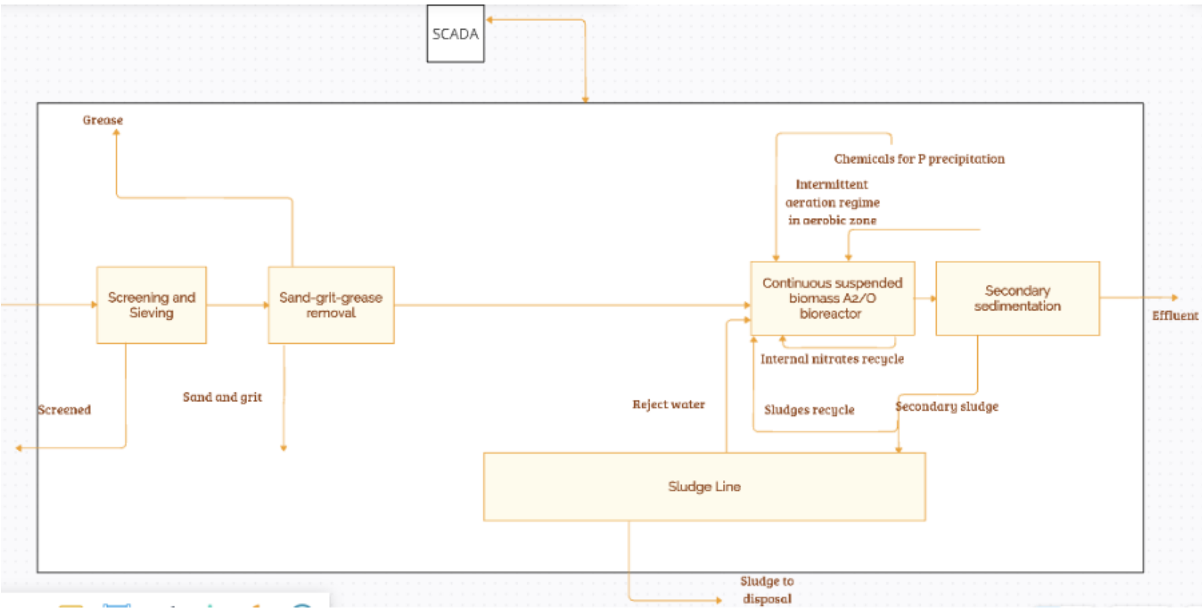

Figure 3.25: Block diagram representative of the water line of group 25 of reference Danish WWTPs

WWTPs of group 25: Ronne

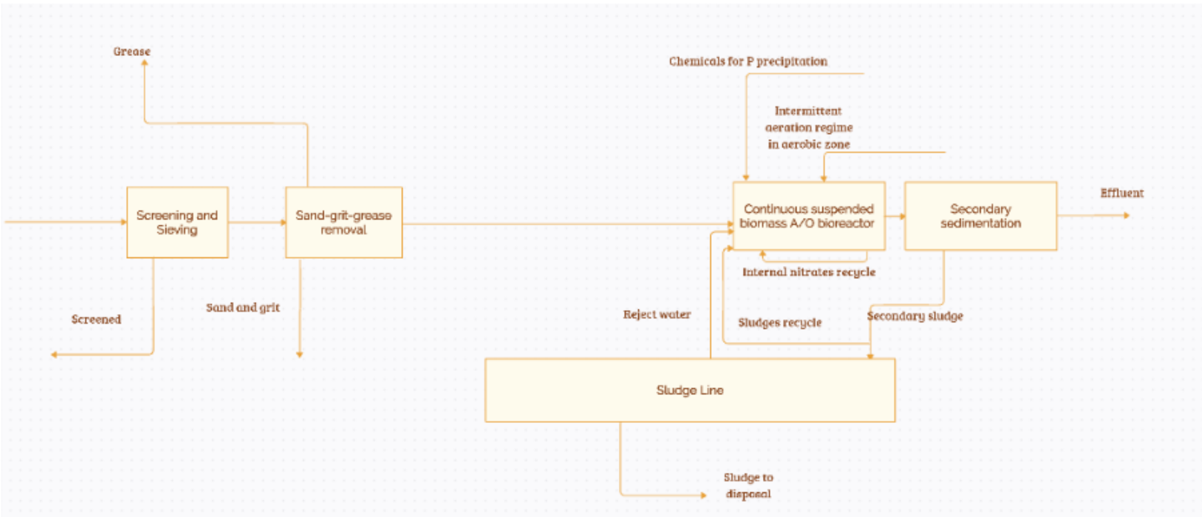

Figure 3.26: Block diagram representative of the water line of group 26 of reference Danish WWTPs

WWTPs of group 26: Stroby; Farevejle; Soro Central; Egebjerg Sud; Strandgarden; Sonderso; Hvide Sande

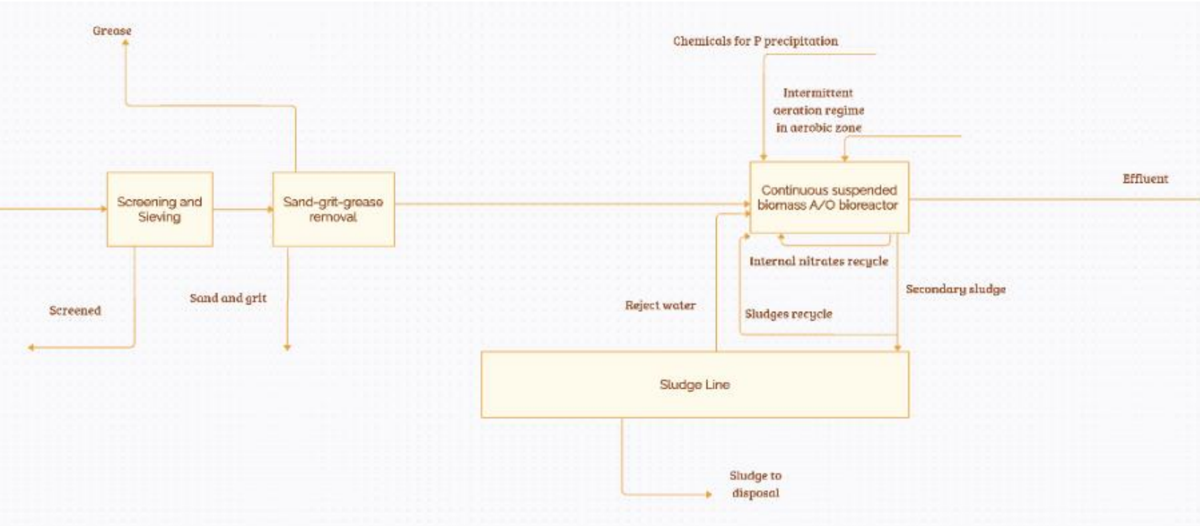

Figure 3.27: Block diagram representative of the water line of group 27 of reference Danish WWTPs

WWTPs of group 27: Rundkobing; Egsmade

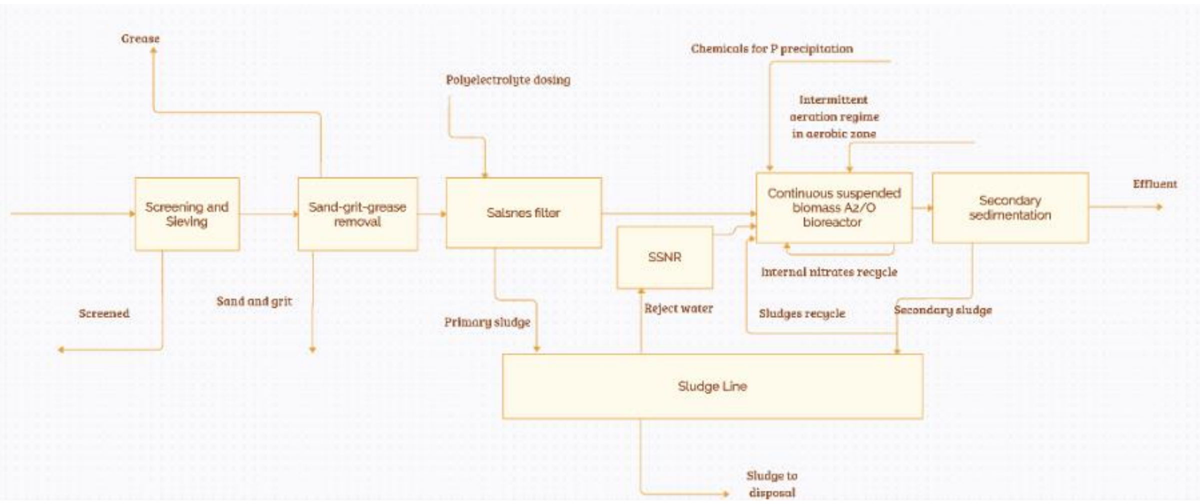

Figure 3.28: Block diagram representative of the water line of group 28 of reference Danish WWTPs

WWTPs of group 28: HCR Sud

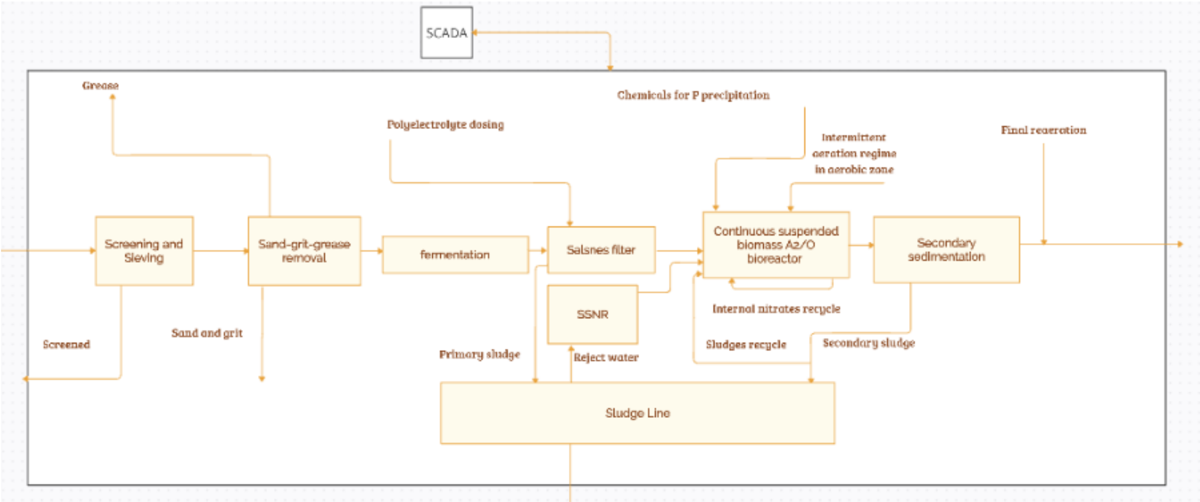

Figure 3.29: Block diagram representative of the water line of group 29 of reference Danish WWTPs

WWTPs of group 29: Ega

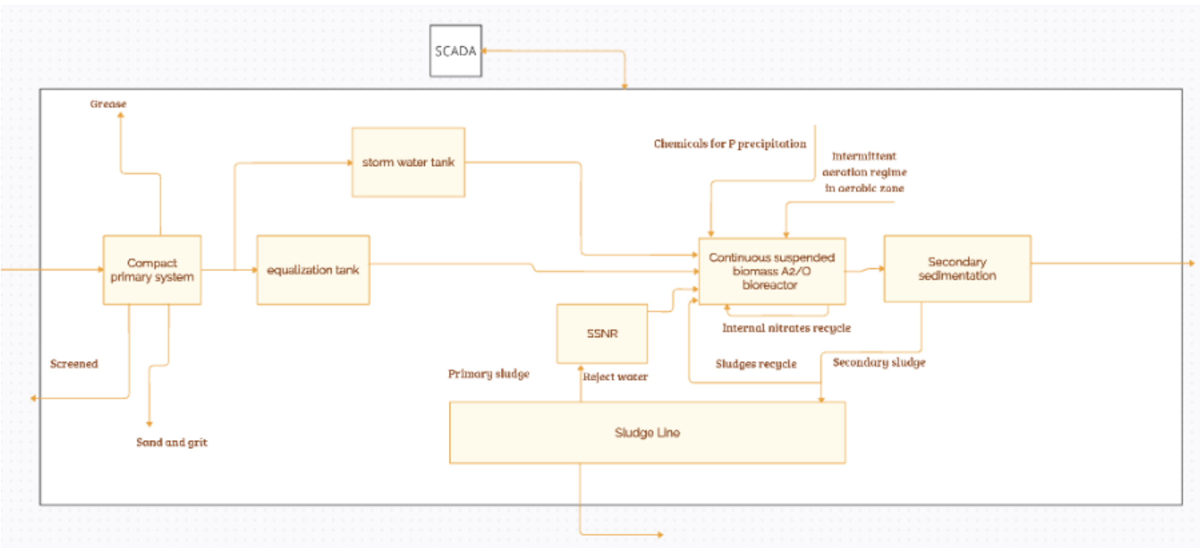

Figure 3.30: Block diagram representative of the water line of group 30 of reference Danish WWTPs

WWTPs of group 30: Grindsted

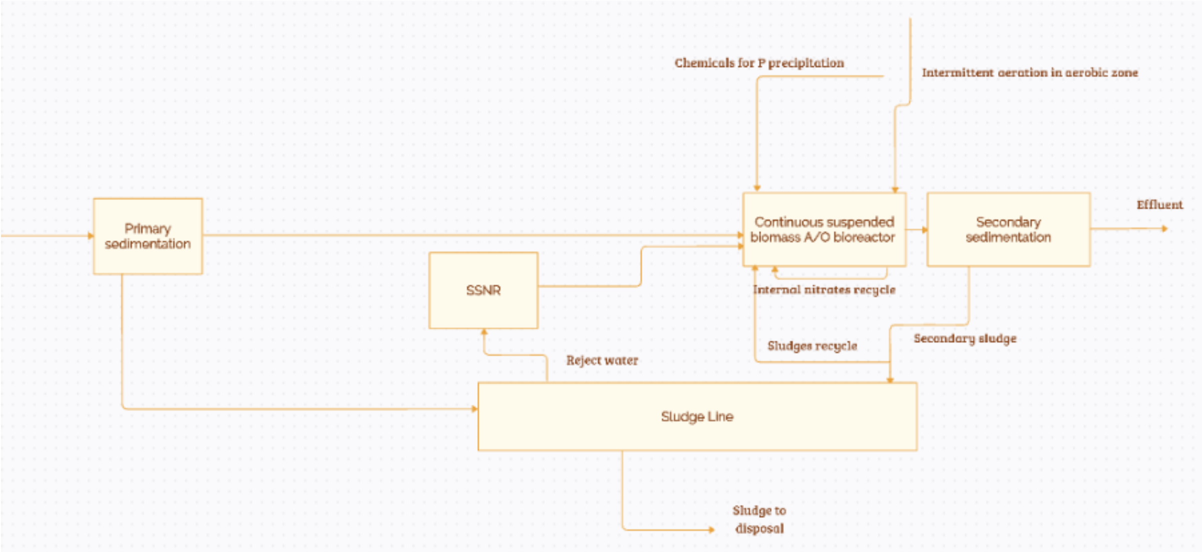

Figure 3.31: Block diagram representative of the water line of group 31 of reference Danish WWTPs

WWTPs of group 31: Holstebro