Determining the Applicability of Advanced Oxidation Processes: A Study of Key Operational Parameters and Field Measurements in Wastewater Treatment Plants in the north of Luxembourg

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Master Thesis

By

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Determining the Applicability of Advanced Oxidation Processes: A Study of Key Operational Parameters and Field Measurements in Wastewater Treatment Plants in the north of Luxembourg

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Abstract

Micropollutants (MPs) in treated wastewater, including pharmaceuticals, personal care products, and industrial chemicals, are an emerging concern for both environmental and human health. Even at very low concentrations, these substances can persist in aquatic ecosystems and disrupt biological processes. Most conventional wastewater treatment plants (WWTPs), especially smaller or rural installations, are not equipped to remove MPs effectively.

This thesis explores the potential of UV/H_2O_2 process, an Advanced Oxidation Processes (AOPs) as a post-treatment step for small and medium-sized WWTPs in Luxembourg. Through field visits, sampling campaigns, and analysis of 15 selected plants, key operational parameters, such as UV transmittance (T10) and inorganic carbon content, were examined to understand their influence on AOP efficiency. In parallel, risk-based assessments and insights from pilot-scale data helped contextualize the treatment potential under realistic conditions.

The goal of this work is to bridge the gap between lab-scale results and on-site feasibility. By identifying practical challenges and key design considerations, this study contributes to future decision-making around AOP implementation for improved micropollutant removal in small-scale wastewater infrastructure.

Résumé

Les micropolluants (MPs) présents dans les eaux usées traitées, notamment les résidus de médicaments, les produits de soins personnels et certains composés issus de l'industrie, représentent une préoccupation croissante pour la santé humaine et les écosystèmes aquatiques. Même à de très faibles concentrations, ces substances peuvent persister dans l'environnement et perturber les processus biologiques. Les stations d'épuration classiques, en particulier les installations de petite et moyenne taille en zones rurales, ne sont généralement pas conçues pour les éliminer efficacement.

Ce mémoire s'intéresse au potentiel des procédés d'oxydation avancée (AOP) basés sur le couple UV/H_2O_2 comme étape de traitement complémentaire dans les petites et moyennes stations d'épuration au Luxembourg. À travers des visites de terrain, des campagnes d'échantillonnage et l'analyse de 15 stations sélectionnées, plusieurs paramètres opérationnels clés, tels que la transmittance UV (T10) et la teneur en carbone inorganique, ont été évalués pour mieux comprendre leur influence sur l'efficacité du procédé. En parallèle, une analyse des risques et des données issues d'études pilotes a permis de replacer les résultats dans un contexte opérationnel réaliste.

L'objectif de ce travail est de contribuer à combler le fossé entre les résultats en laboratoire et la faisabilité sur le terrain. En identifiant les principaux obstacles et les éléments techniques à prendre en compte, cette étude apporte des recommandations utiles pour le déploiement des AOPs et l'amélioration de l'élimination des micropolluants dans les petites infrastructures de traitement des eaux usées.

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List of Abbreviations

MPs – Micropollutants

WWTPs – Wastewater Treatment Plants

AOP – Advanced Oxidation Processes

T10 – UV Transmittance

p.e. – population equivalents

DIC – dissolved inorganic carbon

TSS – Total suspended solids

SBR – Sequencing batch reactor

BIOCOS – C combined system

DOC – dissolved organic carbon

(•OH) – hydroxyl radical

1. Introduction

1.1. Background

MPs are trace organic contaminants such as pharmaceuticals, personal care products, pesticides, and endocrine disruptors. They are now routinely detected in municipal wastewater effluents at nanogram to microgram per liter levels (Zengquan Shu et al., 2016). Even at such low concentrations, they can affect aquatic life and raise concerns for water reuse and ecosystem health. Since conventional wastewater treatment plants (WWTPs) were never designed to remove these compounds, many MPs persist through biological treatment and enter surface waters.

Over the past decade, concern over MPs has increased sharply, leading to stronger regulatory action in Europe. Luxembourg and Switzerland have already tested advanced treatments, and the European Union has recently revised the Urban Wastewater Treatment Directive (2024), introducing a new quaternary stage focused on MP removal. The Directive requires at least 80 % elimination of a defined list of substances for all plants above 150 000 population equivalents (p.e.), with progressive application to smaller facilities down to 10 000 p.e. by 2045. It also applies the “polluter pays” principle through extended producer responsibility and introduces energy-neutrality goals for the wastewater sector (European Union, 2024).

Among the available technologies, AOPs have attracted growing attention. They rely on the generation of hydroxyl radicals (•OH), which can non-selectively oxidize a wide range of organic contaminants. In the UV/H_2O_2 process, hydrogen peroxide is photolyzed under ultraviolet light, producing radicals with a primary quantum yield of about 0.5 (Dongwon Cha et al., 2022). The process efficiency depends on operational parameters such as UV dose and H_2O_2 concentration, but also on the composition of the treated water, including its T_{10}, organic matter, and inorganic carbon content.

Recent laboratory and pilot studies have shown that UV/H_2O_2 significantly improves the degradation of MPs compared to UV alone, although water matrix effects and potential by-products must be carefully managed (Jan Thor et al., 2025); (Zengquan Shu et al., 2016). In Luxembourg, pilot work combining UV/H_2O_2 with granular activated carbon demonstrated high removal efficiencies with minimal ecotoxicity and stable operation (Núnez-Tafalla et al., 2025).

Altogether, these results and the new Directive could help achieve future quaternary treatment goals. To support its implementation, it is necessary to better understand how local water quality, energy use, and operational costs affect its feasibility in small and medium-sized WWTPs under Luxembourgish conditions.

1.2. Objective of the Thesis

The main objective of this thesis is to evaluate the practical feasibility of applying the UV/H_2O_2 AOP for the removal of MPs in small and medium-sized WWTPs located in rural areas of Luxembourg. With the introduction of stricter European regulations requiring improved removal of trace organic contaminants, it has become essential to determine whether such technologies can be effectively integrated into existing small-scale facilities.

This work aims to connect field data with process requirements under realistic operating conditions. It begins by characterizing the effluent quality of fifteen selected WWTPs, focusing on three key parameters that strongly influence UV/H_2O_2 performance: T_{10} at 254 nm, dissolved inorganic carbon (DIC), and total suspended solids (TSS). Together, these parameters provide a detailed picture of the water matrix, determining how efficiently ultraviolet light can penetrate the effluent and how •OH are generated or scavenged during treatment.

Using the measured values, the study then estimates the energy demand associated with implementing the UV/H_2O_2 process at each site, based on the UV dosage and hydrogen peroxide dosage required under the observed conditions. By combining these experimental results with energy needs, the thesis seeks to deliver a practical assessment of the operational feasibility, energy implications, and scalability of UV/H_2O_2 systems in small and medium-sized WWTPs across Luxembourg.

1.3. Thesis Structure

This thesis is divided into six chapters, each building on the previous one to develop a complete understanding of the study and its outcomes.

Chapter 1 introduces the context of the work, presents the main objectives, and outlines the structure of the thesis.

Chapter 2 serves as the literature review. It summarizes the current knowledge on MPs in wastewater, discusses their environmental impact and regulatory framework in Europe and Luxembourg, and reviews the main treatment technologies available for their removal, with particular attention to AOP and the UV/H_2O_2 system.

Chapter 3 describes the research methodology. It explains how the study was designed, how the fifteen WWTPs were selected, and how the sampling and analytical procedures were carried out.

Chapter 4 provides a presentation of the selected WWTPs, including their treatment technologies, design capacities, and contextual factors that may affect the implementation of advanced treatment processes.

Chapter 5 presents and discusses the results. It includes the measured parameters (T_{10}, DIC and TSS), the energy and cost estimations, and an interpretation of how these factors influence the feasibility of the UV/H_2O_2 process in small and medium-sized WWTPs.

Finally, Chapter 6 concludes the work by summarizing the main findings, discussing their practical implications, and proposing perspectives for future implementation of advanced oxidation in Luxembourgish WWTPs.

2. Literature Review

2.1. Micropollutants Problematic: European and Luxembourgish Context

Context

Over the last two decades, scientists, regulators, and water managers have become increasingly concerned about the presence of MPs in the aquatic environment. These substances include pharmaceuticals, personal care products, pesticides, industrial additives, flame retardants, and endocrine-disrupting compounds. Although typically found at very low concentrations, ranging from nanograms to micrograms per liter, they can still cause toxic or hormonal effects in aquatic organisms and, in some cases, pose long-term risks to human health ((Núnez-Tafalla et al., 2025); (Zengquan Shu et al., 2016)).

Conventional WWTPs were designed to remove organic matter, nutrients, and pathogens, but not synthetic trace contaminants. Many MPs are persistent and poorly biodegradable, allowing them to pass through the treatment process and enter rivers, lakes, and groundwater largely unchanged ((Núnez-Tafalla et al., 2025); (Jan Thor et al., 2025)). Their continuous release into the environment has led to the development of new treatment approaches and, more recently, to significant changes in water policy across Europe.

European Regulatory Framework

The European Union's response to this growing issue has evolved from scientific awareness to concrete regulation. The original Urban Wastewater Treatment Directive (91/271/EEC), adopted in 1991, focused mainly on reducing organic matter, nutrients, and pathogens in wastewater discharges. At that time, MPs were not recognized as a concern and were therefore not addressed.

In the years that followed, the EU introduced a mechanism under the Water Framework Directive to monitor chemicals of emerging concern. Via successive "watch-lists", starting in 2015, pharmaceuticals and other MPs were progressively added to the substances under surveillance.

After years of accumulating evidence on the persistence and ecological impact of MPs, the European Union adopted Directive (EU) 2024/3019, which entered into force on 1 January 2025. This revision introduces, for the first time, a mandatory quaternary treatment stage specifically targeting the removal of MPs (European Union, 2024).

The Directive requires at least 80% removal efficiency for a defined list of substances, including widely detected pharmaceuticals and chemicals of concern listed in Annex I of the respective Directive.

Implementation will be gradual. Large WWTPs (≥150,000 p.e.) must achieve compliance by 2045, with earlier deadlines for very large plants. Smaller plants (≥10,000 p.e.) located in sensitive areas are also required to meet the same removal targets where their discharges pose risks to human health or the environment.

Beyond MPs, the Directive strengthens nutrient controls by tightening emission limits for nitrogen and phosphorus and sets an energy-neutrality goal for the wastewater sector by 2045. It also applies the polluter pays principle, making producers of pharmaceuticals and cosmetics responsible for at least 80% of the costs associated with quaternary treatment and related monitoring (European Union, 2024).

Luxembourgish Context

Luxembourg's national water policy aligns closely with the new European framework. The Plan National de Gestion de l'Eau (PNG-Eau) outlines key actions to improve water quality, including the reduction of hazardous substances and MPs. While the country is still at an early stage of implementing quaternary treatment, the Ministry of the Environment has recognized the need to prepare both large urban WWTPs and smaller rural facilities for compliance with the new Directive.

Pilot projects supported by public authorities and local syndicates, such as SIDEN and SIDEST have already tested advanced treatment technologies, including AOPs and granular activated carbon (InfoGreen, 2025). These projects have generated valuable data on the occurrence and removal of common MPs such as diclofenac, carbamazepine, and sulfamethoxazole, all of which appear in the EU's priority list.

Luxembourg's wastewater network is characterized by many small and medium-sized WWTPs serving dispersed rural populations. Ensuring that these facilities can meet future quaternary treatment requirements will therefore require tailored solutions, both technically and economically, to achieve compliance while maintaining operational sustainability.

2.2. Conventional technologies used in small-medium sized WWTP in SIDEN

Before evaluating the feasibility of UV/H_2O_2 in decentralized wastewater treatment, it is essential to understand the existing biological treatment technologies in place. Each technology shapes the effluent quality (e.g., T_{10}, DIC, TSS), the hydraulic behavior, the footprint available for retrofit, and therefore the overall compatibility with a quaternary step. For this reason, a brief overview of the most installed systems in small and medium-sized WWTPs is necessary to contextualize their performance and better interpret the results obtained in this study.
Small to medium-sized WWTPs often rely on compact, efficient systems that balance treatment performance with space and operational simplicity. Here are key technologies used in such contexts:

- Activated Sludge Process

The activated sludge process, first developed in 1914 and tested at the Manchester–Davyhulme WWTP, is a biological wastewater treatment method that accelerates the decomposition of organic matter through the action of concentrated microorganisms. In its modern form, it typically operates as a continuous-flow system with separate clarifiers and sludge recirculation, or as a fill-and-draw system such as a sequencing batch reactor (SBR) (Cristina Tuser , 2021).

Wastewater enters an aerated tank, where flocs of bacteria remain suspended and degrade organic pollutants under aerobic conditions, converting them into water, CO_2, and new biomass. The biomass is separated in a secondary clarifier, with part of the settled sludge recycled to maintain the microbial population and the remainder removed as waste sludge. The treated effluent can then undergo polishing before discharge (Cristina Tuser , 2021).

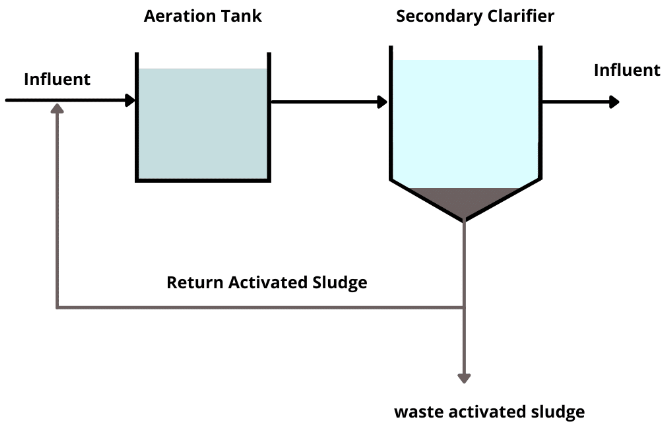

Figure 1: Activated sludge process

- Sequencing Batch Reactor

A SBR is a fill-and-draw wastewater treatment system used for both municipal and industrial applications. It can operate with a single tank or multiple tanks, depending on plant size and influent characteristics. Treatment is carried out in discrete cycles, each comprising five phases:

1. Fill – Raw wastewater enters a tank containing residual biomass from the previous cycle. This can occur without mixing (static fill), with mixing (mixed fill), or with aeration (aerated fill).
2. React – Biological treatment continues under controlled conditions, which may be aerobic, anoxic, or anaerobic, to achieve organic and nutrient removal.
3. Settle – Flow is halted, allowing solids to settle under quiescent conditions.
4. Draw – The clarified supernatant is decanted, typically over a period that can exceed 30% of the total cycle time.
5. Idle – A transitional phase between draw and fill, during which sludge is wasted, and biomass can be mixed.

This cyclic operation allows SBRs to provide both biological treatment and clarification in the same tank, making them well-suited for small to medium-sized WWTPs where footprint and operational flexibility are important (Saleha Kuzniewski, 2024).

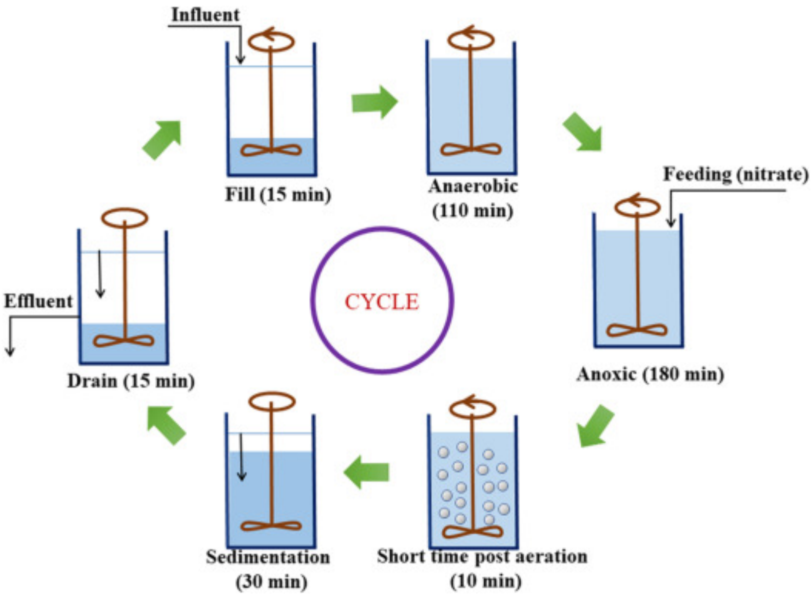

Figure 2 : SBR CYCLE

- Immersion Disk or Rotating biological contactor

A rotating biological contactor is a wastewater treatment system that uses a series of partially submerged rotating discs to support the growth of a microbial biofilm. The discs, usually made of corrosion-resistant plastic, provide a surface for microorganisms to attach and form biofilms. As the discs rotate, the biofilm alternately contacts the wastewater and the air, allowing microorganisms to degrade organic matter while being continuously supplied with oxygen. This process promotes efficient biological treatment with low energy requirements and simple operation, making rotating biological contactor suitable for small to medium-sized WWTPs.

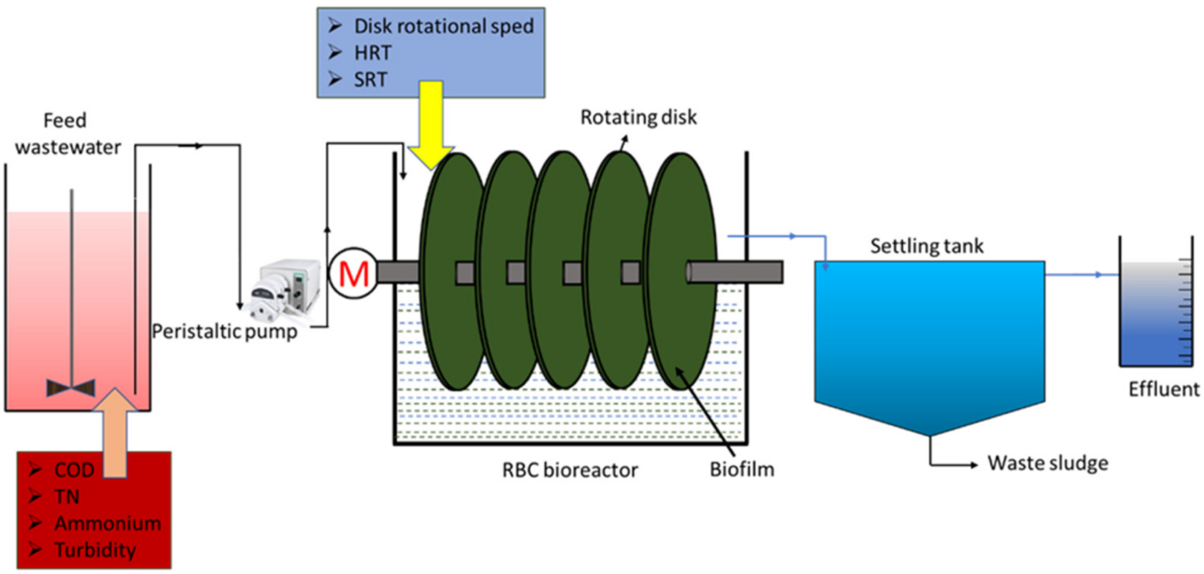

Figure 3 : RBC Process

- BIOCOS® (Biological Combined System)

BIOCOS® is a compact and cost-effective alternative to conventional activated sludge systems, combining the principles of activated sludge with granular sludge technology in a cyclic, air-driven process. The system operates without pumps or submerged mechanical parts, relying entirely on-air control for mixing, sludge transfer, and settling.

Key advantages include reduced footprint due to rectangular tanks, up to 25% lower energy use, minimal maintenance, and proven reliability with over 150 installations worldwide. Developed at the University of Innsbruck, BIOCOS® is particularly suited for small and medium-sized WWTPs with limited space and infrastructure (Treatment, 2025).

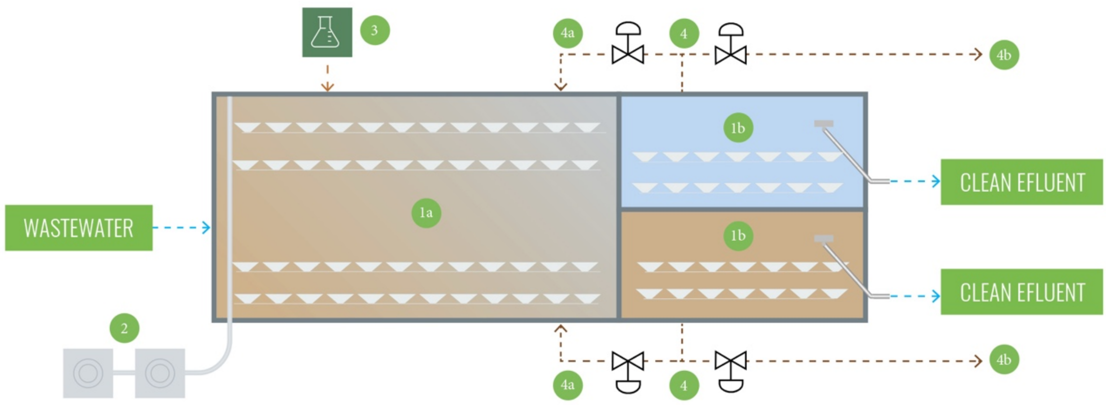

Figure 4 : BIOCOS Process

- 1b-1c alternating sludge recycling and settling tanks (ALT 1-2)
- 2 Blowers to aeration (1a) and air-driven RAS-recycle and reactor mixing
- 3 chemical dosing system (if necessary)
- 4 sludge removal
- 4a recirculated aerobic sludge
- 4b wasted aerobic sludge

2.3. Micropollutant-removal process

Several treatment processes have been investigated for the removal of MPs from wastewater. They can be broadly grouped into filtration, adsorption, oxidation, and biological methods, each offering specific advantages and drawbacks depending on the characteristics of the compounds and the treatment goals. Figure 5 summarizes these techniques, highlighting their main advantages and limitations in terms of efficiency, stability, energy consumption, and environmental impact.

Filtration methods, such as reverse osmosis, nanofiltration, ultrafiltration, and microfiltration, are highly effective for removing many compounds and provide stable performance. However, they are separation rather than degradation processes. The generation of a concentrated by-product and their high energy demand make them expensive and less sustainable for large-scale application (Elizabeta Domínguez et al., 2025).

Adsorption processes using granular or powdered activated carbon are among the most established and cost-effective techniques. They efficiently remove a wide range of MPs, especially hydrophobic and neutral compounds, but require regular replacement or regeneration of the carbon media. Powdered activated carbon treatment also generates sludge that must be managed, increasing operational costs and energy use. The presence of organic matter can further reduce adsorption efficiency by competing for active sites.

Oxidation processes, particularly ozonation and UV/H_2O_2, are very flexible and capable of degrading a broad spectrum of MPs through direct and radical-mediated reactions. Their main limitation lies in the incomplete mineralization of certain compounds, which can lead to the formation of unknown transformation products with potential environmental risks. These systems also involve relatively high energy consumption (Dongwon Cha et al., 2022).

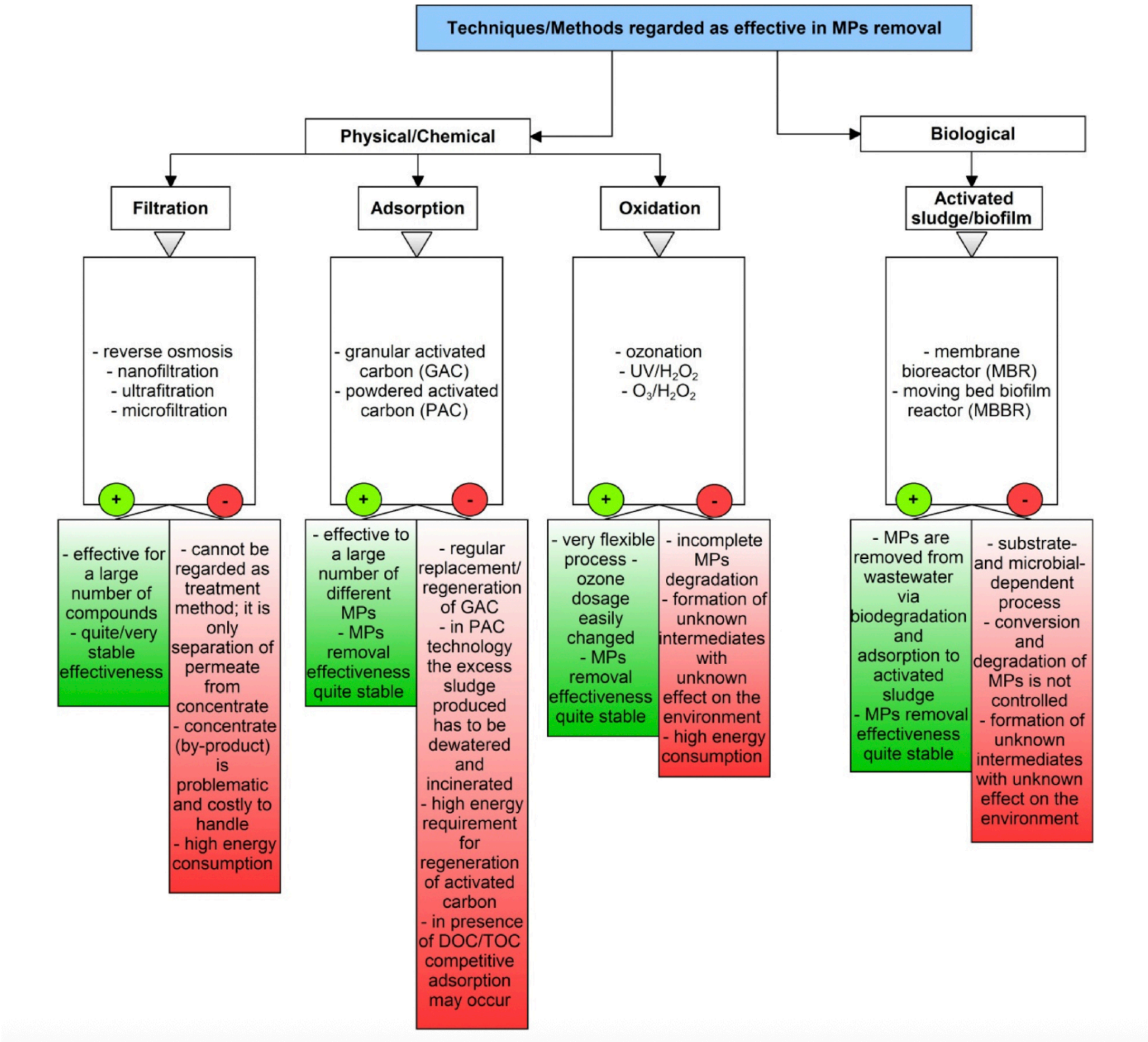

Figure 5: Techniques regarded as effective in MPs removal (Kosek et al., 2020)

Finally, biological treatments, such as membrane bioreactors or moving bed biofilm reactors, remove MPs mainly through biodegradation and adsorption to sludge. Their performance depends strongly on the microbial community and the biodegradability of the target compounds. While effective for certain MPs, many persistent compounds remain unaffected.

In practice, advanced oxidation and adsorption are currently regarded as the most promising options for upgrading existing WWTPs to meet future micropollutant-removal requirements, as they can be integrated relatively easily into conventional treatment lines.

2.4. Advanced Oxidation Processes: Principles and Benefits

AOPs are treatment technologies specifically designed to degrade persistent organic MPs that conventional biological and physicochemical treatment steps often fail to remove. Their core principle is the generation of highly reactive •OH, which have a high oxidation potential (2.8 V) and can react non-selectively with a broad spectrum of organic compounds at near diffusion-controlled rates (David B. Miklos et al., 2018).

•OH can break down MPs into smaller, more biodegradable compounds or completely mineralize them to CO_2, water, and inorganic salts. This oxidative mechanism is effective for a wide variety of MPs, including pharmaceuticals, pesticides, industrial chemicals, and endocrine-disrupting compounds, which often persist through conventional treatment due to their low biodegradability and chemical stability (David B. Miklos et al., 2018).

AOPs can be implemented through different oxidant–energy combinations. These include ozone-based processes (e.g.,O_3/H_2O_2), UV-based processes (e.g., UV/H_2O_2, UV/O_3), electrochemical AOPs (eAOPs), catalyst-assisted AOPs such as Fenton and photo-Fenton, and other physical AOPs. (David B. Miklos et al., 2018). Among them, UV/H_2O_2, discussed in Section 2.5, is one of the most mature options for full-scale MP removal in wastewater.

The key benefits of AOPs for MP removal are:

- Broad-spectrum effectiveness, they are effective against a wide variety of organic pollutants regardless of structure.
- Rapid reaction kinetics, •OH react very quickly with most MPs, allowing short contact times.
- Toxicity reduction, they can degrade hazardous compounds and transformation products into less harmful substances.
- Compatibility with existing infrastructure, AOP units can be added as a polishing step in conventional WWTPs.

However, AOP performance depends heavily on the water matrix composition. Constituents such as dissolved organic carbon (DOC), bicarbonates, and chlorides can act as radical scavengers, reducing the number of •OH radicals available for MP degradation. Additionally, some AOPs require significant energy input (UV lamps, ozone generation) and may produce by-products that require additional treatment (David B. Miklos et al., 2018).

In the context of the revised Urban Wastewater Treatment Directive (EU 2024/3019), which introduces stricter limits and a quaternary treatment requirement for MP removal, AOPs represent a promising option, particularly for WWTPs that require high treatment performance and adaptable integration into existing layouts.

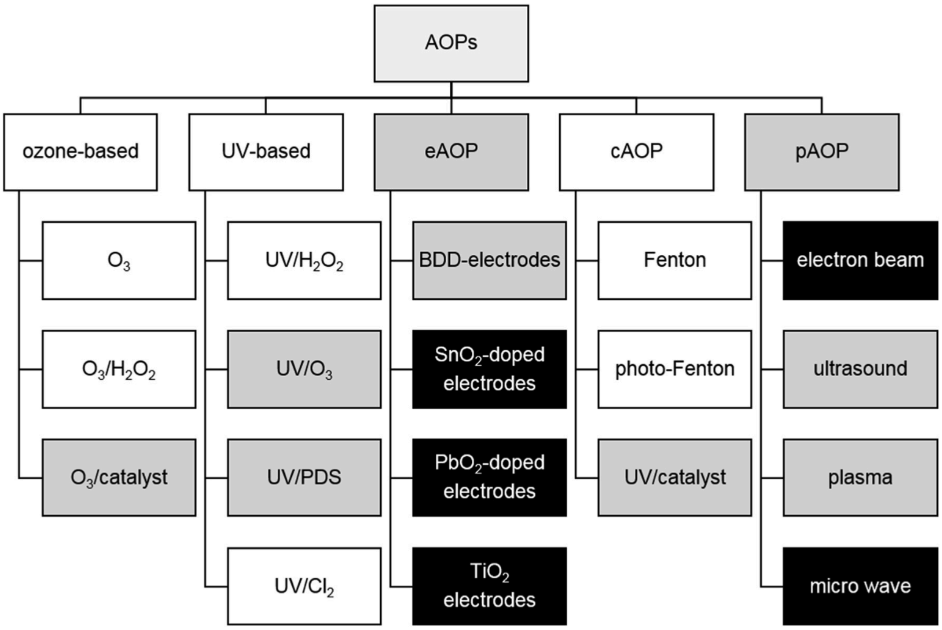

Figure 6 : AOPs (David B. Miklos et al., 2018)

Figure 6 presents a broad overview and classification of AOPs. Individual processes are marked as established at full-scale (white), investigated at lab- and pilot-scale (grey), and tested at lab-scale (black) (adapted from (David B. Miklos et al., 2018)).

2.5. UV/H_2O_2 Process

The UV/H_2O_2 process is one of the most established AOPs for the degradation of organic MPs in wastewater. It relies on the combined action of ultraviolet light and hydrogen peroxide to generate •OH, which are extremely reactive and capable of oxidizing a wide range of organic compounds (Zengquan Shu et al., 2016). These radicals are non-selective and react within milliseconds, breaking down complex molecules into simpler or more biodegradable forms (Dongwon Cha et al., 2022).

In this process, hydrogen peroxide acts as the radical precursor. When exposed to ultraviolet radiation, typically at 254 nm, it absorbs photons and undergoes photolysis according to the following reaction:

$$H_2O_2 + hv \rightarrow 2 \bullet OH.$$

Each molecule of hydrogen peroxide yields two •OH, which then react with the surrounding organic contaminants through various mechanisms such as hydrogen abstraction, addition to double bonds, and electron transfer (Dongwon Cha et al., 2022). The reaction rate and efficiency depend primarily on the UV fluence, wavelength, and the optical properties of the water (Jan Thor et al., 2025).

The effectiveness of the UV/H_2O_2 process is influenced by several water quality parameters. High concentrations of natural organic matter suspended solids, or inorganic carbon can reduce T_{10} and act as scavengers for •OH, lowering treatment efficiency (Zengquan Shu et al., 2016). Similarly, turbidity and color in the effluent limit light penetration, requiring higher UV doses and consequently higher energy consumption. The process is therefore most effective in secondary or tertiary effluents that are already clarified and have relatively high T_{10} (Jan Thor et al., 2025).

Compared to other AOPs the UV/H_2O_2 system has several practical advantages. It operates at ambient pressure and temperature, produces no residual oxidants in the treated water, and can be easily integrated into existing UV disinfection systems with limited structural modifications (Zengquan Shu et al., 2016). It also allows precise control of reaction conditions through the adjustment of UV intensity and H_2O_2 dosage. However, the process requires careful optimization to balance energy use, chemical consumption, and target pollutant removal, since both under- and overdosing of hydrogen peroxide can reduce overall efficiency (Dongwon Cha et al., 2022).

A key design parameter for UV/H_2O_2 systems is the UV dose or fluence, usually expressed in mJ/cm^2. This value represents the cumulative energy received by the water and determines the extent of radical formation. For practical applications, the relationship between fluence, oxidant dose, and pollutant removal follows pseudo-first-order kinetics, which allows process modelling and scale-up for different plant capacities (Jan Thor et al., 2025).

Overall, the UV/H_2O_2 process is a compact, flexible, and effective technology that can degrade a wide range of MPs when properly optimized. Its performance strongly depends on the quality of the treated effluent and on maintaining appropriate operational conditions. These characteristics make it a promising option for future implementation in small and medium-sized WWTPs, particularly where space and retrofitting feasibility are important considerations ((Zengquan Shu et al., 2016); (Dongwon Cha et al., 2022); (Jan Thor et al., 2025)).

Critical characteristics of water matrix

The performance of the UV/H_2O_2 process is strongly influenced by the composition and quality of the treated effluent. Both chemical and physical characteristics of the water matrix determine how effectively •OH are generated and utilized for micropollutant degradation.
In AOPs such as UV/H_2O_2, •OH are the main oxidative species responsible for the breakdown of MPs. These radicals are extremely reactive but non-selective, meaning they also react with other compounds present in the water matrix. In treated wastewater, a large fraction of these reactions occurs with effluent organic matter rather than with the target pollutants. According to (Olya S. Keen et al., 2023), up to 95% of •OH scavenging can result from dissolved organic matter. This implies that in real wastewater conditions, most of the generated radicals may be consumed by background organic matter, leaving only a small fraction available for micropollutant oxidation. Consequently, the efficiency of AOPs in full-scale operation is often considerably lower than in controlled laboratory experiments, highlighting the importance of characterizing effluent organic matter concentrations during design and optimization.

Beyond chemical composition, the optical and physical properties of the effluent also play a decisive role. Parameters such as T_{10}, turbidity, and TSS determine how much ultraviolet light can penetrate the water column. High turbidity or elevated TSS increase light scattering and absorption, reducing the fluence available for hydrogen peroxide photolysis. Likewise, color and dissolved organic matter can attenuate UV radiation, requiring higher energy input to achieve similar treatment performance. Ensuring a clarified effluent before oxidation is therefore essential to maintain efficiency, limit energy consumption, and ensure stable operation in full-scale applications ((Zengquan Shu et al., 2016); (Dongwon Cha et al., 2022); (Jan Thor et al., 2025)).

3. Methodology

3.1. Field Sampling and Measurements

Sampling campaigns were carried out between late April and mid-July, with three separate campaigns conducted during this period. Most sampling took place in the morning. I drove to each of the selected WWTPs to collect treated effluent samples at the outlet of the WWTP.

At the beginning of each sampling day, the spectrophotometer was calibrated using distilled water. This procedure involved filling the cuvette with distilled water, pressing the calibration button, and confirming that the T_{10} value read 100%. The calibration step ensured that subsequent measurements were accurate.

At each WWTP, a water sample was collected, and the cuvette was rinsed with distilled water before testing. The T_{10} value of the treated effluent was then measured on site using the calibrated device. Figure 7 shows the portable spectrophotometer used for the measurements.

Figure 7: portable spectrophotometer

3.2. Laboratory Analyses

After each sampling day, the collected effluent was transported to the university laboratory. On arrival, each sample was filtered through a 0.45 µm membrane to remove particulate matter before carbon analysis. The filtration apparatus was assembled as shown in Figure 10. Figure 9 shows the moment of filtering the water through the 0.45 µm membrane. The filtrate was subsequently analyzed for total carbon and DIC using the TOC analyzer shown in Figure 10.

Figure 8 : Filtering

Figure 9 : Filtration apparatus

TSS were not measured during the first sampling campaign. This parameter was added from the second campaign onward, once early results indicated that particulate matter could influence UV absorbance and radical scavenging. As a result, TSS data are available for only two of the three campaigns at each WWTP. For TSS determination, filters were weighed before filtration (Figure 13), and a known volume of sample was filtered (Figure 12). To speed up the filtration process, a pump was used to create a vacuum in the bottle holding the filter. After filtration, the filters were dried in an oven at approximately 120 °C and then re-weighed. TSS was calculated from the mass difference between the dry filter before and after filtration, relative to the filtered volume.

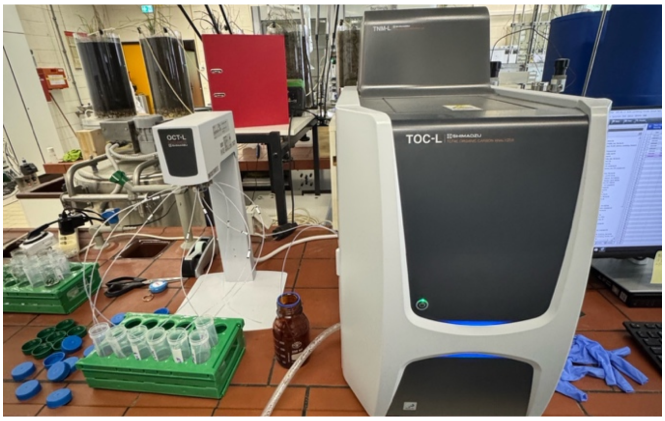

Figure 10 : TOC analyzer

Figure 11: TSS Filtering

Figure 12: Filter before filtration and after

3.3. Calculations

The energy demand for each WWTP was estimated using the same calculation approach applied in the operation of the UV/H_2O_2 pilot plant conducted at the Heiderscheidergrund WWTP. This method provides a consistent framework for evaluating the energy requirements of the UV system across plants of different sizes and flow conditions.

In the Heiderscheidergrund pilot, the UV system consisted of four lamps of 600 W each, operating to treat a flow rate of 12.3 m^3/h. This configuration served as the reference point for scaling the energy consumption to the other WWTPs.

To estimate the number of UV lamps required for each plant, a rule of three was applied, proportionally adjusting the lamp configuration to the design flow rate of each WWTP. This allowed for an initial estimation of the total installed UV power per site, assuming comparable reactor geometry and UV efficiency.

Once the total installed power was determined, the energy demand (kWh/m³) for each WWTP was calculated according to the following relationship:

$$E = \frac{P_{total}}{Q_{treated}}$$

where:

- E = specific energy consumption (kWh/m³),
- P_{total} = total UV lamp power required (kW),
- Q_{treated} = average flow rate of the WWTP (m³/h).

The resulting energy values were then converted to €/m³ by applying the unit electricity cost used in the pilot project (0,20 e/kWh based on Luxembourg's industrial energy tariff). This provides an estimate of the operational cost contribution from energy consumption for each WWTP.

The estimation of hydrogen peroxide demand was carried out following the procedure provided by Núñez-Tafalla for the Heiderscheidergrund pilot plant. In this method, hydrogen peroxide is assumed to be dosed as a 35% commercial solution, corresponding to a concentration of:

$$C_{\text{stock}} = 350\ 000 \text{ mg/L}$$

and the unit cost of the stock solution is 300 €/m³.

For each WWTP and scenario (best and worst), the calculation consists of four main steps:

- Determine the daily treated volume from the nominal plant flow:

$$V_{\text{day}} = Q \times 3600 \times 24 [\text{L/day}]$$

- Calculate the volume of 35% stock solution required per day, based on the H_2O_2 dose D (mg/L):

$$V_{H_2O_2,\text{day}} = \frac{D \times V_{\text{day}}}{C_{\text{stock}}} \text{ [L/day]}$$

- Compute the daily cost as:

$$C_{\text{day}} = V_{H_2O_2,\text{day}} \text{ [m}^3\text{/day]} \times 300 \text{ €/m}^3$$

- Calculate the specific cost per cubic meter of treated water:

$$C_{H_2O_2} = \frac{C_{\text{day}}}{V_{\text{day}}/1000} \text{ [€/m}^3\text{]}$$

Where:

• Q = plant flow rate (L/s)

• D = applied H_2O_2 dose (mg/L)

• V_{day} = daily treated volume (L/day)

• $V_{H_2O_2,\text{day}}$ = daily volume of 35% H_2O_2 stock solution (L/day)

• C_{day} = daily chemical cost (€)

• $C_{H_2O_2}$ = chemical cost per cubic meter (€/m^3)

• $C_{\text{stock}} = 350\ 000$ mg/L = H_2O_2 concentration in the 35% stock solution

4. Selected WWTPs

4.1. Selection of WWTPs

Fifteen WWTPs were selected in collaboration with SIDEN, focusing on small- and medium-sized facilities in northern Luxembourg, with some located in more isolated areas. The selection included plants with varying capacities and influent characteristics, from sites treating primarily domestic wastewater to larger facilities receiving significant industrial discharges. Differences in plant size, operational conditions, and treatment configurations were considered to ensure the sample covered a broad range of situations. None of the selected sites currently operate a quaternary treatment stage. The geographical distribution of these WWTPs is shown in Figure 7, where yellow dots mark their locations within the SIDEN network.

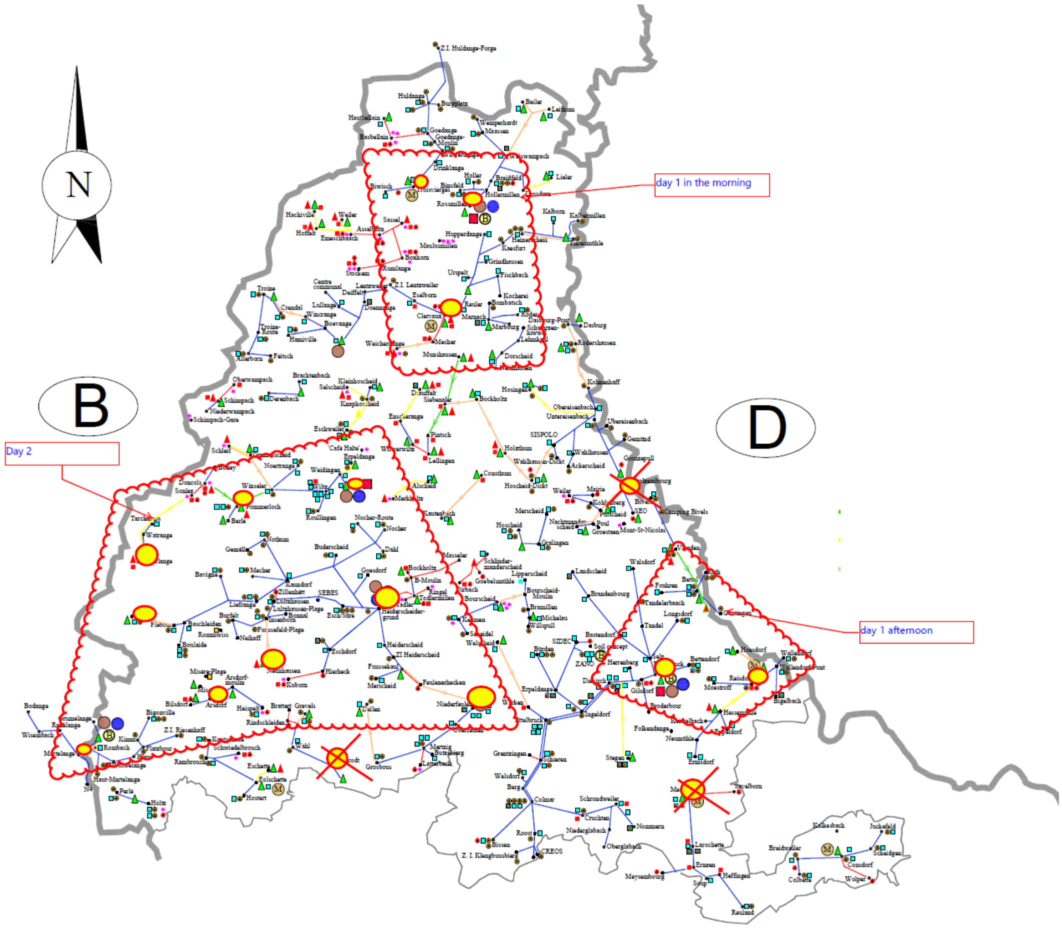

Figure 13 : WWTPs Locations

4.2. Overview of the wastewater treatment in northern Luxembourg

The northern region of Luxembourg is characterized by a mix of small towns, villages, and some larger urban areas with industrial zones. This diverse settlement pattern results in varied wastewater production across the region, influenced by tourism, cross-border commuting, and seasonal population changes. Wastewater collection and treatment in the area are coordinated by the Syndicat Intercommunal de Dépollution des Eaux Résiduaires du Nord (SIDEN), which operates a dense and complex network of facilities and infrastructure.

As of the latest data, SIDEN manages 79 biological treatment plants, 33 mechanical treatment plants, and more than 320 wastewater collection structures, along with numerous pumping stations. The network is designed to handle both urban wastewater and stormwater through a combination of unitary systems, where rainwater and wastewater are conveyed together, and separate systems, where clean rainwater is discharged directly to the environment while wastewater is sent to treatment plants (SIDEN, Les communes membres du SIDEN, 2025).

To cope with heavy rain events, the region is equipped with stormwater overflows and stormwater retention basins. These structures temporarily store excess flow to prevent hydraulic overloading of the sewer network and WWTPs. In many cases, only the first flush of runoff, typically the most polluted, is retained for treatment, while subsequent, less contaminated flows are discharged to water bodies (SIDEN, Collecte des eaux usées, 2025).

Pumping stations are used to lift wastewater above its current level, allowing it to travel long distances in pressurized pipes or by gravity through low-gradient pipelines. This is particularly important in hilly areas and for connecting smaller or isolated communities to the main treatment facilities (SIDEN, Collecte des eaux usées, 2025).

This infrastructure ensures that wastewater from domestic, industrial, and touristic activities is collected, conveyed, and treated before being returned to the environment. However, most existing plants are designed for conventional pollutant removal and will require upgrades to meet the stricter micropollutant removal targets set by the revised Urban Wastewater Treatment Directive (EU 2024/3019).

4.3. Overview of the selected WWTPs

This study focuses on 15 WWTPs located in the northern region of Luxembourg, all characterized by small to medium treatment capacities. Their p.e. range from 350 to 130,000, reflecting a mix of rural communities, tourism-driven areas, and small urban agglomerations. The nominal flow rates (Q^{TW}) span from 3.5 L/s up to 375 L/s, which provides a representative dataset to assess the feasibility of advanced oxidation in decentralized contexts. Most facilities rely on conventional activated sludge, which remains the dominant treatment technology in Luxembourg. However, the dataset also includes alternative configurations such as immersion discs, Biocos, and SBR. This technological diversity enables a broader comparison of hydraulic performance and water-quality conditions relevant for UV/H_2O_2 applications.

Table 1 provides an overview of the 15 WWTPs selected for this study, summarizing their p.e., nominal flow rates, and installed treatment technologies. These characteristics are essential for evaluating both the hydraulic context and the potential feasibility of implementing UV/H_2O_2 post-treatment at each site. A more detailed description of each WWTP, including influent characteristics and service area information, is provided in the annexes.

Nr.	WWTP Name	p.e.	QTW (L/s)	Treatment Technology
1	KA Martelange	7100	70	Activated sludge
2	KA+RÜB Troisvierges	9000	60	Activated sludge
3	KA Rossmillen	5000	28	Activated sludge
4	KA+RÜB Wiltz	16500	88	Activated sludge
5	KA Bettel	9000	60	Immersion discs
6	KA+RÜB Pommerloch	1500	20	Activated sludge
7	KA+RÜB Clervaux	9700	53	Activated sludge
8	KA Reisdorf-Wallendorf	4300	10	Activated sludge
9	KA Arsdorf	1500	18.5	Biocos
10	KA Surré	450	5	SBR
11	KA+RÜB Neuhausen	350	3.5	Biocos
12	KA Harlange	2500	46	Activated sludge
13	KA Feulen	9000	64	Biocos
14	KA Bleesbruck	130000	375	Activated sludge
15	KA Heiderscheidergrund	12000	29	Activated sludge

Table 1: WWTPs Overview

5. Results and Discussion

The sampling campaign provided an overview of the key physicochemical parameters influencing the applicability of UV/H_2O_2 treatment, including the T10, DIC, and TSS. The results, reflect the variability in effluent quality among the 15 WWTPs included in this study. These data form the basis for assessing how each site's water quality could affect the efficiency of AOPs, particularly regarding light penetration (which affect to the •OH generation), and •OH scavenging effects.

In addition to characterizing effluent quality, the results section also includes the estimation of operational energy demand and associated costs for each WWTP. By combining the measured T10 values with modeled UV doses, H_2O_2 doses, and plant-specific flow rates, it was possible to approximate both the energy consumption and chemical dose linked to the implementation of a UV/H_2O_2 system. These cost estimations provide a first insight into the economic feasibility of applying AOPs in small- and medium-sized WWTPs across northern Luxembourg.

5.1. UV Transmittance

T10 is a key reference parameter for assessing the feasibility of applying UV/H_2O_2 treatment, as it directly reflects the capacity of the effluent to allow UV radiation to penetrate through the water column. High transmittance values indicate clearer water and therefore higher UV efficiency, whereas low T10 values suggest the presence of organic or particulate matter that can absorb or scatter UV light, reducing treatment performance.

In Table 2, the average T10 values measured for each WWTP are presented, providing an overview of the effluent transmittance characteristics across the sampling period. A supplementary table (Table 7) includes all individual measurements from the three sampling campaigns, allowing for a more detailed view of temporal variations observed at each site.

	WWTP Name	Average T10 (%)
1	KA Martelange	69,6
2	KA+RÜB Troisvierges	78,8
3	KA Rossmillen	74,1
4	KA+RÜB Wiltz	72,3
5 & 6	KA Bettel before Pond	60,1
	KA Bettel after Pond	61,1
7	KA+RÜB Pommerloch	56,3
8	KA+RÜB Clervaux	69,5
9	KA Reisdorf-Wallendorf	80,3
10	KA Arsdorf	79,3
11	KA Surré	76,9
12	KA+RÜB Neuhausen	78,7
13	KA Harlange	70,4
14	KA Feulen	78
15	KA Bleesbruck	77
16	KA Heiderscheidergrund	79,2

Table 2: Average T10

Figure 14 shows the T10 values of the different WWTPs represented in the form of a bubble chart. The size of each bubble is proportional to the treatment capacity of the corresponding WWTP, allowing a quick visual comparison of plant sizes. This representation highlights both the variation in T10 values among plants and the influence of the applied treatment technology.

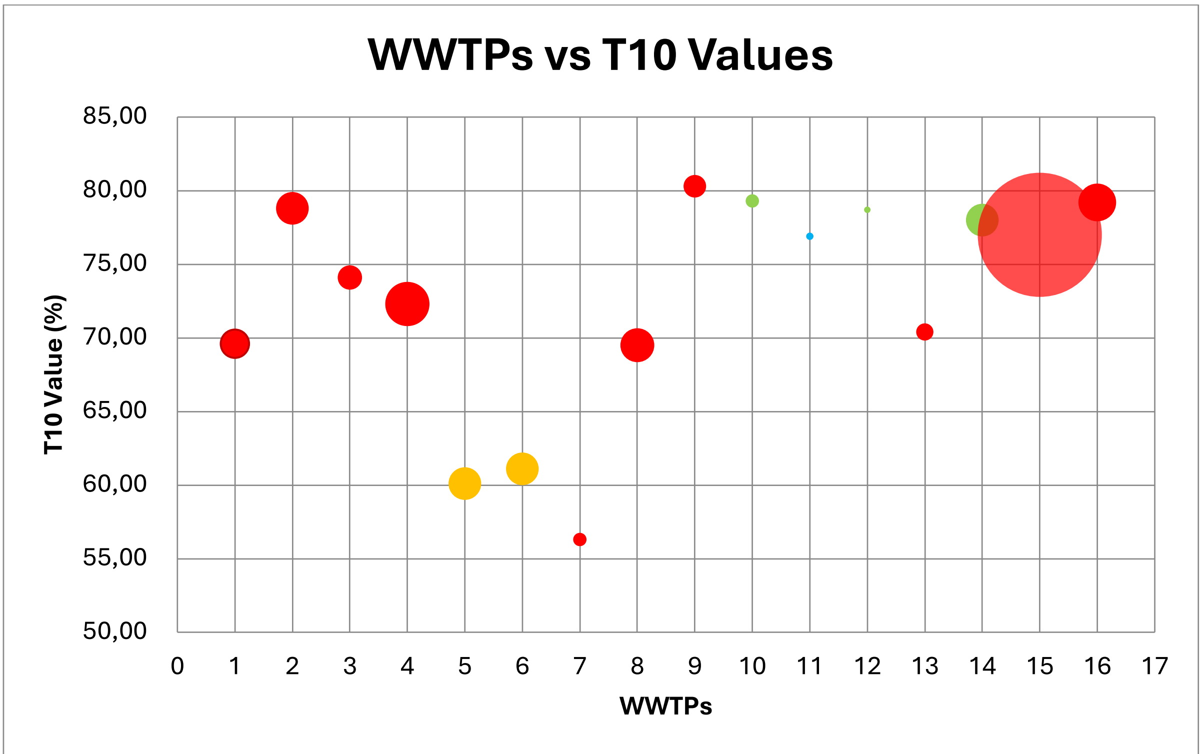

Figure 14: X-axis, WWTPs ordered as in the index in Table 2, Y-axis T_{10} values in percentage. Color of the bubbles, treatment technology: red, conventional activated sludge treatment, orange immersion disc technology, green Biocos systems, and blue SBR.

In general, T_{10} values above approximately 70 % can be considered good, while values below around 60 % indicate poor hydraulic behavior, with part of the flow likely passing through the reactor too quickly.

The average T_{10} values across the 15 monitored WWTPs ranged between 56.3 % at Pommerloch and 80.3 % at Reisdorf-Wallendorf (Table 2, Figure 14). Activated sludge plants (red bubbles) showed the widest variation, from relatively low values such as Pommerloch (56.3 %) to higher values like Reisdorf-Wallendorf (80.3 %) and Heiderscheidergrund (79.2 %).

The particularly low value observed at Pommerloch could be related to the fact that, in recent years, a significant number of new buildings, shopping centers, and offices have been constructed around the area. The WWTP itself is relatively small, and the increased load may have exceeded its optimal capacity, potentially leading to hydraulic overloading and reduced residence time.

The immersion disc plants (orange bubbles, Bettel before pond and Bettel after pond) recorded among the lowest T_{10} values (60.1 % and 61.1 %). However, as only one WWTP with this technology was included in the study, the relevance of this observation remains uncertain and should be interpreted with caution, as it does not provide sufficient representativity.

Biocos plants (green bubbles, e.g. Clervaux at 69.5 % and Bleesbruck at 77.0 %) showed more consistent results in a mid-to-high range, while the SBR system at Neuhausen (blue bubble) achieved one of the highest values (78.7 %). Although these findings suggest that Biocos and SBR technologies can generally ensure stable hydraulic conditions and good T_{10}, the limited number of installations means that the conclusions should be considered indicative rather than definitive. In contrast, conventional activated sludge plants display a much wider range of T_{10} values, from low to very good, placing them at the extremes of the observed performance spectrum.

This broad variability in activated sludge systems can be explained by the fact that they are the most widespread and the most diverse technology in terms of configuration, operational control, sludge age, and clarifier design. Factors such as hydraulic overloading, insufficient sludge settling performance, or high infiltration water can significantly reduce transmittance in these systems. When well-operated, however, activated sludge plants can also achieve high effluent clarity and rank among the best performers in the dataset.

Overall, while activated sludge remains the dominant technology, SBR and Biocos systems showed more consistently high T_{10} values, generally ranging between 70 and 80 %, whereas the immersion disc configuration performed the weakest. This suggests that newer or more structurally controlled technologies tend to ensure better hydraulic behavior and therefore more reliable performance regarding T_{10}.

When considering the size of the WWTPs, larger facilities such as Feulen (78.0 %) and Heiderscheidergrund (79.2 %) generally displayed higher T_{10} values, supporting the idea that larger-scale plants benefit from more stable hydraulic behavior due to their higher buffering capacity and longer retention times.

The T_{10} measurements were conducted under mostly dry-weather conditions. However, during the second and third sampling campaigns, rainfall occurred either during the night or on the day before sampling at several sites, notably at Martelange and Pommerloch. This likely influenced the results by increasing inflow and partially diluting the effluent, which can shorten the effective residence time in the reactor. Rainwater intrusion can also disturb the secondary clarifier, resuspend fine particles and increase turbidity, which in turn reduces T_{10}.

5.2. Dissolved Inorganic Carbon

The DIC values measured across the WWTPs provide important insight into the presence of scavengers in the water matrix, which play a significant role in the UV/H_2O_2 process. High DIC concentrations indicate elevated levels of bicarbonate and carbonate species, which are known to act as •OH scavengers, thereby reducing the efficiency of UV/H_2O_2 treatment. This not only affects the oxidation performance but also increases maintenance requirements. High DIC can promote the formation of mineral scale, mainly calcium carbonate, on the quartz sleeves surrounding the UV lamps, leading to fouling that reduces T_{10} and necessitates more frequent cleaning. In addition to this operational burden, higher fouling also implies the need for an increased UV dose, a higher H_2O_2 dosage, or both, to achieve the same treatment performance and reach the target 80 % removal efficiency.

Consequently, DIC emerges as a key parameter to evaluate before scaling up AOP applications. Systems with consistently high DIC should undergo further assessment to confirm process feasibility and to determine whether pre-treatment or operational adjustments are required to maintain stable and efficient performance. Table 3 presents the DIC concentrations measured at each WWTP.

	WWTP Name	DIC (mg/L)
1	KA Martelange	15,9
2	KA+RÜB Troisvierges	20,6
3	KA Rossmillen	30
4	KA+RÜB Wiltz	26,9
5 & 6	KA Bettel before Pond	15,3
	KA Bettel after Pond	28,2
7	KA+RÜB Pommerloch	21,0
8	KA+RÜB Clervaux	35,5
9	KA Reisdorf-Wallendorf	61,1
10	KA Arsdorf	27,2
11	KA Surré	26,3
12	KA+RÜB Neuhausen	34,6
13	KA Harlange	11,2
14	KA Feulen	37,5
15	KA Bleesbruck	65,6
16	KA Heiderscheidergrund	19,6

Table 3: DIC concentration

Figure 15 presents the DIC values (mg/L) measured at the different WWTPs, where bubble size indicates the plant capacity and color represents the treatment technology. The results show a broad variability across sites, ranging from very low DIC values such as in Harlange (11.2 mg/L) and Martelange (15.9 mg/L) to very high concentrations observed in Bleesbruck (65.6 mg/L) and Reisdorf-Wallendorf (61.1 mg/L). Intermediate values were found in Clervaux (35.5 mg/L), Feulen (37.5 mg/L), and Neuhausen (34.6 mg/L).

WWTPs using activated sludge treatment (red bubbles) cover almost the entire range, from some of the lowest values (Harlange) to the highest (Bleesbruck), showing that DIC levels are not primarily determined by the treatment technology itself. Instead, they appear to be more strongly influenced by local water characteristics such as groundwater infiltration, the use of carbonate-rich materials in the catchment, or the contribution of industrial discharges. Smaller plants using immersion discs (orange bubbles) showed moderate DIC concentrations, such as Bettel before pond (15.3 mg/L) and Bettel after pond (28.2 mg/L). Biocos (green) and SBR (blue) plants also presented values in a similar intermediate range (around 25–35 mg/L), suggesting that technology may play a secondary role, possibly through differences in aeration intensity or CO_2 stripping, but that the dominant factor remains the regional hydrochemistry and influent composition.

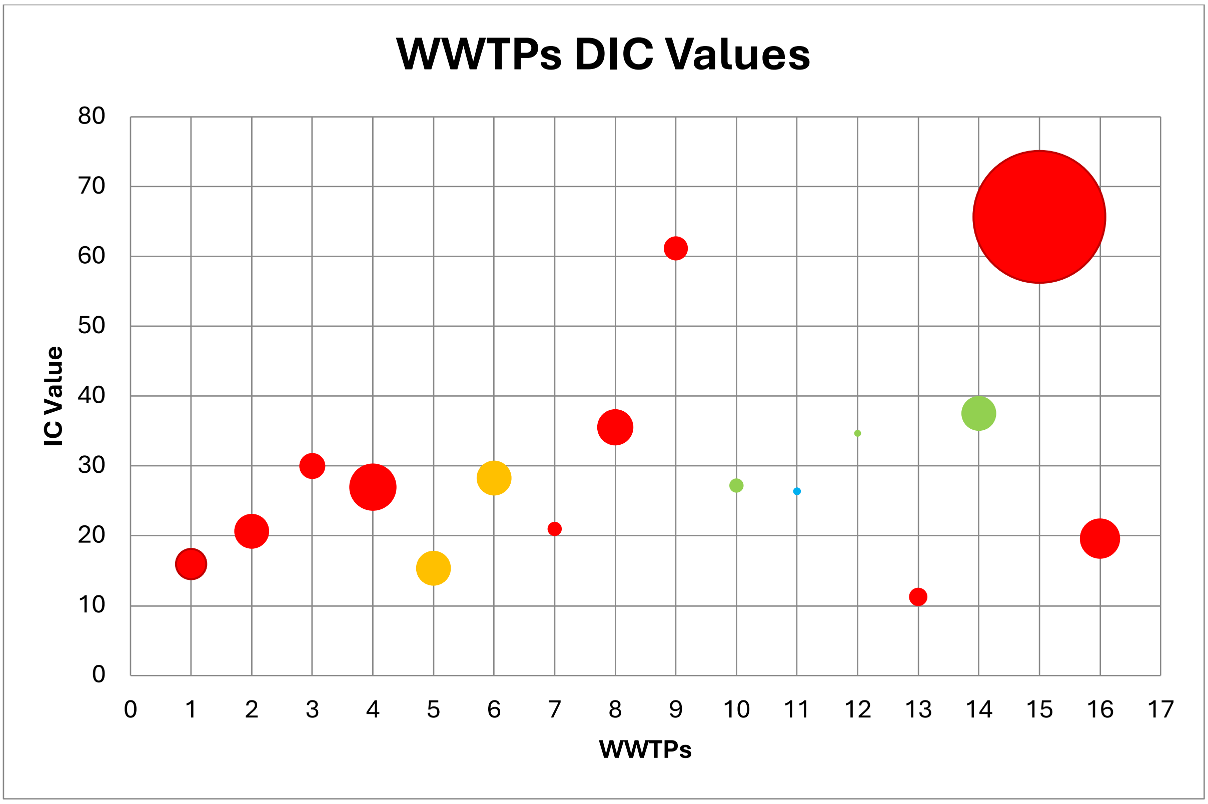

Figure 15: DIC representation. Color of the bubbles, treatment technology: red, conventional activated sludge treatment, orange immersion disc technology, green Biocos systems, and blue SBR.

Overall, the data suggest that treatment technology alone does not have a direct influence on DIC, as differences appear to stem mainly from regional hydrochemistry and the level of groundwater or surface water infiltration entering the sewer network. In Luxembourg, variations in DIC concentrations are largely governed by the underlying geology rather than by treatment configuration. The country can be divided into two main geological regions: the northern Oesling and the southern and eastern Gutland.

The Oesling region, where WWTPs such as Harlange, Martelange, Pommerloch, Clervaux, Troisvierges, Surré, and Heiderscheidergrund are located, is primarily composed of Devonian schists and sandstones. These formations are poor in carbonates and typically lead to softer groundwater with lower bicarbonate content, which is consistent with the relatively low to moderate DIC values measured in these plants (between approximately 11 and 38 mg/L).
In contrast, the Gutland region, particularly the eastern part, where Bleesbruck, Reisdorf-Wallendorf, and Feulen are situated, is dominated by Triassic and Jurassic formations rich in

limestones and dolomites, such as the Muschelkalk and Luxembourg Sandstone (Overview of the geology of Luxembourg, 2023). These carbonate-rich layers naturally increase groundwater hardness and bicarbonate concentrations through the dissolution of calcium and magnesium carbonates, which in turn elevate DIC levels when groundwater infiltrates the sewer system (Yonca Pinar Ingin et al., 2024). This geological contrast aligns well with the results of this study, as the highest DIC concentrations were found in eastern WWTPs such as Bleesbruck (65.7 mg/L) and Reisdorf-Wallendorf (61.2 mg/L), while the lowest values were recorded in northern plants such as Harlange (11.3 mg/L) and Martelange (16.0 mg/L).

These findings confirm that regional geology and groundwater composition are the dominant factors influencing DIC variability in Luxembourgish WWTPs, with carbonate-rich formations in the east leading to systematically higher DIC levels than those observed in the siliceous terrains of the north.

5.3. Total Suspended Solids

For the TSS, the analysis was carried out only from the second sampling campaign onward. During some of the first sampling events, visible suspended solids were observed in the treated effluent, which is not expected under normal operating conditions, as effluent quality standards legally limit the concentration of solids in discharged wastewater. According to the European Urban Wastewater Treatment Directive (91/271/EEC), the concentration of suspended solids in treated wastewater must not exceed 35 mg/L for plants serving more than 10,000 p.e., and 60 mg/L for plants between 2,000 and 10,000 p.e., with minimum removal efficiencies of 90% and 70%, respectively.

The presence of visible solids during the first campaign therefore indicated a temporary deviation from these standards, most likely caused by short-term operational disturbances or maintenance activities. To ensure that the results reflected representative and compliant effluent conditions, TSS measurements were included only from the second and third sampling campaigns, when effluent quality had stabilized.

Table 4 presents the TSS concentrations measured at each WWTP during these later campaigns.

	WWTP Name	TSS (mg/L)
1	KA Martelange	6
2	KA+RÜB Troisvierges	6
3	KA Rossmillen	1,8
4	KA+RÜB Wiltz	4,2
5 & 6	KA Bettel before Pond	6,9
	KA Bettel after Pond	3
7	KA+RÜB Pommerloch	5,8
8	KA+RÜB Clervaux	1,3
9	KA Reisdorf-Wallendorf	2,8
10	KA Arsdorf	4,5
11	KA Surré	12,2
12	KA+RÜB Neuhausen	2,0
13	KA Harlange	8,0
14	KA Feulen	4,0
15	KA Bleesbruck	3,6
16	KA Heiderscheidergrund	5,1

Table 4: TSS concentration

Figure 16 presents the TSS concentrations measured across the sampled WWTPs. In this figure, bubble size represents the plant treatment capacity, while bubble color indicates the treatment technology.

Overall, the data highlight that TSS concentrations vary significantly between plants and may have important implications for the UV/H_2O_2 process. Higher solids content can increase light scattering and absorption, reduce UV penetration and thus lower treatment efficiency. Moreover, high TSS are typically associated with higher organic content, which can act as •OH scavengers, further decreasing oxidation performance. Elevated TSS may also correspond to lower T_{10} values, since particles can alter hydraulic flow patterns and promote turbidity. Maintaining low solids levels is therefore essential to ensure both efficient hydraulic behavior and optimal AOP performance.

The results show notable variability between sites, ranging from as low as 1.3 mg/L at Clervaux (activated sludge) to 12.2 mg/L at Surré (SBR). Other low values were found at Rossmillen (1.8 mg/L) and Neuhausen (2 mg/L), both relatively small plants, while higher concentrations were recorded at Harlange (8 mg/L) and Bettel before pond (6.9 mg/L).

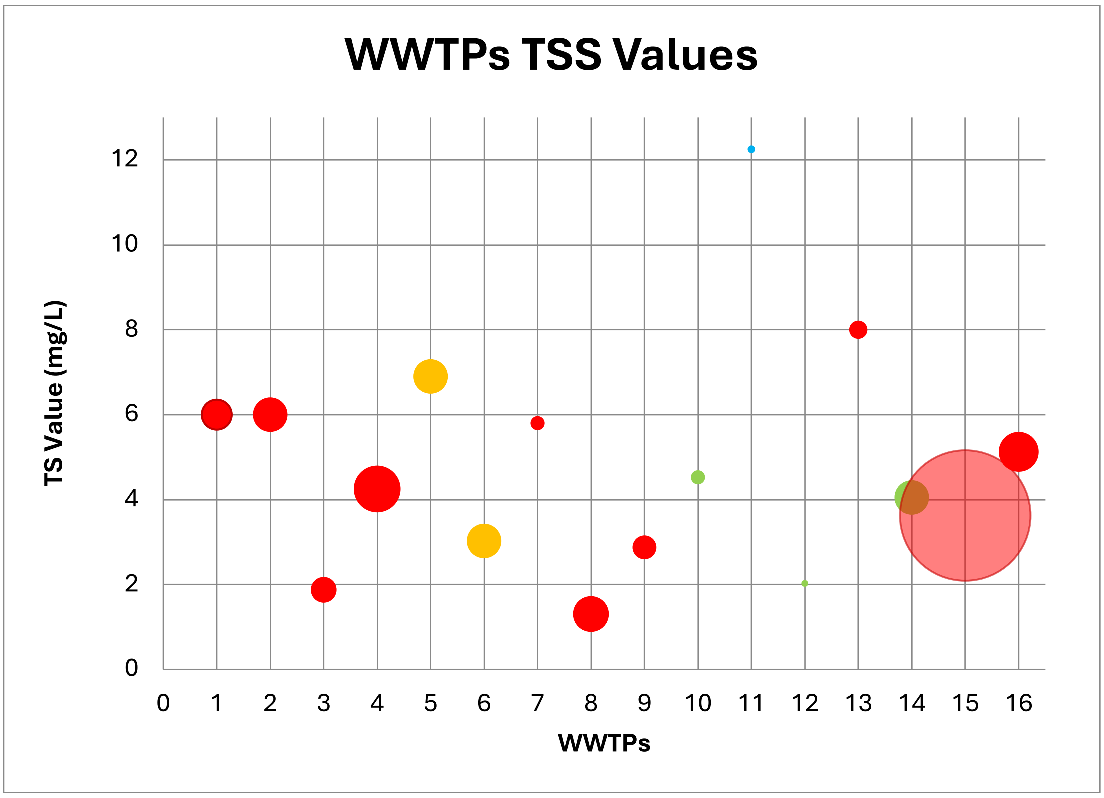

Figure 16 : TSS representation. Color of the bubbles, treatment technology: red, conventional activated sludge treatment, orange immersion disc technology, green Biocos systems, and blue SBR.

These differences cannot be directly attributed to treatment technology alone, as both SBR and activated sludge systems appear across the full range of values. Instead, they likely reflect operational and environmental factors such as hydraulic fluctuations, sludge settling efficiency, and recent rainfall events. For instance, Surré, despite being an SBR plant, showed the highest TSS, which could be linked to partial sludge carryover or disturbances in the sedimentation phase, conditions that occasionally occur in small batch-operated systems. In Harlange, the elevated solids concentration might result from limited hydraulic retention or occasional sludge blanket instability, both of which are common in compact activated sludge configurations. Similarly, Bettel before pond exhibited higher TSS values likely because of resuspension from the preceding treatment stages, as solids can accumulate and be intermittently released from the pond inlet area.

In contrast, larger WWTPs such as Heiderscheidergrund (5.1 mg/L) and Bleesbruck (3.6 mg/L) maintained moderate TSS levels despite their size, which suggests that good sludge management and stable settling conditions are more decisive for effluent clarity than capacity or technology type. A weak but visible trend can also be observed when comparing TSS and

T_{10}: plants with higher solids content generally show lower T_{10}, confirming that suspended particles interfere with UV penetration and may reduce the efficiency of the UV/H_2O_2 process.

In some cases, rainfall prior to sampling could also have influenced TSS concentrations by increasing hydraulic loads and resuspending deposited solids, particularly in smaller plants with limited buffering capacity. This effect is often linked to the secondary clarifier, where excess inflow or turbulence caused by rainwater infiltration can disturb the sludge blanket and lead to the carryover of fine solids into the treated effluent.

5.4. Service Area and Plant Size: Influence on Results

The characteristics of each WWTP, particularly their service area and p.e., help explain some of the variability observed in DIC and TSS values. Plants serving mixed or partly industrial catchments, such as Wiltz and Feulen, showed higher DIC and TSS, likely due to inputs from workshops, schools, and small industries, which increase both the mineral and organic load of the influent. In contrast, plants in predominantly domestic or rural areas tended to show lower and more stable concentrations.

In Clervaux, moderate fluctuations in DIC likely reflect the influence of tourism, as the seasonal variation in population temporarily increases water use and organic load. However, the seasonal impact across all sites remained limited, with no clear differences detected between sampling campaigns, suggesting that short-term variability did not significantly affect overall trends.

Finally, while Bettel receives part of its flow from a small cross-border area, this had no measurable effect on the effluent quality parameters analyzed in this study, and the catchment's influence appears minimal compared to the general variability between plants.

Geographical distribution and scale also help explain the observed differences. Smaller WWTPs such as Pommerloch (T_{10} = 56.3 %, TSS = 5.8 mg/L), Surré (T_{10} = 76.9 %, TSS = 12.2 mg/L), and Neuhausen (T_{10} = 78.7 %, TSS = 2 mg/L), which serve only local populations, are more sensitive to short-term fluctuations caused by rainfall or seasonal peaks, such as tourism in the northern regions. This sensitivity is reflected in the wider range of T_{10} and TSS values observed between sampling campaigns. In contrast, larger WWTPs such as Bleesbruck (T_{10} = 77.0 %, TSS = 3.63 mg/L) and Wiltz (T_{10} = 72.3 %, TSS = 4.2 mg/L), which treat wastewater from several municipalities, showed more stable hydraulic and compositional conditions. Their higher and more constant inflow volumes appear to buffer daily and seasonal variability, resulting in more consistent effluent quality across campaigns.

Altogether, the results confirm that catchment characteristics, plant size, and local context play a decisive role in effluent quality and, consequently, in the feasibility of advanced oxidation. Clear spatial patterns were observed: WWTPs located in the eastern part of Luxembourg, such as Bleesbruck (DIC = 65.7 mg/L) and Reisdorf-Wallendorf (DIC = 61.2 mg/L), presented the highest DIC concentrations, consistent with the region's carbonate-rich geology. In contrast, plants in the northern Oesling region, such as Harlange (DIC = 11.3 mg/L) and Martelange (15.9 mg/L), showed significantly lower values, reflecting the influence of schist and sandstone formations poor in carbonates.

Plant size also had a clear impact. Larger WWTPs such as Bleesbruck (T_{10} = 77.0 %, TSS = 3.6 mg/L) and Heiderscheidergrund (T_{10} = 79.2 %, TSS = 5.1 mg/L) showed stable effluent quality with little variability between sampling campaigns (typically <3%), whereas smaller plants like Pommerloch (T_{10} = 56.3 %, TSS = 5.8 mg/L) and Surré (T_{10} = 76.9 %, TSS = 12.3 mg/L) exhibited larger fluctuations of up to 10–15%, especially following rainfall events. This indicates that larger hydraulic volumes buffer variations more effectively, ensuring consistent operating conditions and better treatment stability.

The type of catchment further explains the observed variability. Industrial or mixed urban–rural catchments, such as Wiltz (DIC = 27.0 mg/L) and Feulen (37.5 mg/L), showed slightly higher DIC and TSS due to discharges from workshops, schools, and light industries, which add both inorganic and organic loads. Conversely, rural and domestic catchments, such as Martelange or Arsdorf, produced more stable effluents with lower DIC and TSS. In touristic areas such as Clervaux, seasonal peaks related to tourism were reflected in moderate variations in DIC (around 10 mg/L between campaigns), although these remained within the typical measurement uncertainty.

From a technological perspective, the results suggest that SBR and Biocos systems achieved the most consistent hydraulic performance, with T_{10} values typically between 70–80% and moderate DIC levels (25–40 mg/L). Activated sludge systems covered a much wider range, from the lowest (Pommerloch, 56.3%) to the highest (Reisdorf-Wallendorf, 80.3%), highlighting the influence of operational conditions and catchment composition. The immersion disc technology, represented only by Bettel, showed weaker T_{10} values (60–61%), though this conclusion should be interpreted cautiously due to the limited sample size.

The integration of T_{10}, DIC, and TSS parameters shows that effluent quality, and thus AOP applicability, depends as much on local environmental and operational factors as on the treatment technology itself. Stable, large, and carbonate-rich systems present both opportunities and challenges: while they ensure reliable hydraulics, they also require higher oxidant doses to overcome scavenging effects. Conversely, small rural systems are easier to retrofit but remain sensitive to external disturbances. Understanding these interdependencies is essential for designing realistic and site-adapted advanced oxidation strategies in Luxembourg's wastewater network.

5.5. Cost Analysis

The assessment of operational costs provides an essential perspective for evaluating the practical feasibility of implementing the UV/H_2O_2 process in small and medium-sized WWTPs. Beyond treatment efficiency, the economic dimension strongly determines whether advanced oxidation can be realistically integrated into existing facilities. In this context, energy consumption represents the dominant cost factor, followed by chemical consumption (H_2O_2). Overall, this cost evaluation aims to highlight how differences in scale, process design, and local conditions influence the economic performance of AOP implementation in Luxembourgish WWTPs.

Table 5 summarizes the estimated operational costs for the UV/H_2O_2 process across all monitored WWTPs, distinguishing between the worst and best scenarios. These scenarios were modeled using Van Remmen's design data, which provide a simplified framework for preliminary cost estimation. However, this model should not be considered definitive or used as a basis for design or investment decisions, as it does not account for DIC concentrations and considers only T_{10} values when estimating UV dose requirements. Consequently, the resulting costs offer only an indicative comparison between sites and represent a first-order approximation of the potential operational range.

The table 5 below summarizes the operational settings used to estimate the performance of the UV/H_2O_2 process across the 15 WWTPs. For each plant, two conditions were modelled, based on reference values provided by Van Remmen. The worst-case scenario corresponds to higher UV fluence and increased H_2O_2 dosage, reflecting more challenging water matrix conditions. In contrast, the best-case scenario assumes a lower UV fluence and reduced oxidant demand, representing optimized operation. These modeled parameters were then used as the basis for calculating the energy consumption and chemical cost per cubic meter of treated water.

	Worst scenario		Best scenario	
	UV dose	H2O2 dose	UV dose	H2O2 dose
KA Martelange	5900	29	4300	9
KA+RÜB Troisvierges	4900	27	3400	7
KA Rossmillen	4900	27	3500	7
KA+RÜB Wiltz	5600	28	4000	8
KA Bettel before Pond	7500	31	5800	13
KA Bettel after Pond	7300	30	5600	12
KA+RÜB Pommerloch	8300	32	6600	15
KA+RÜB Clervaux	5900	29	4400	9
KA Reisdorf-Wallendorf	4700	27	3300	7
KA Arsdorf	4800	27	3400	7
KA Surré	4800	27	3300	7
KA+RÜB Neuhausen	4900	27	3400	7
KA Harlange	5800	29	4300	9
KA Feulen	4900	27	3500	7
KA Bleesbruck	4800	27	3300	7
KA Heiderscheidergrund	4800	27	3400	7

Table 5: reference values provided by Van Remmen

In table 6, orange cells correspond to the worst-case conditions, combining higher H_2O_2 dosages with less favorable hydraulic or matrix characteristics, while green cells indicate the best-case scenario, where the process operates under optimal conditions with lower chemical and energy demand.

	H2O2 Cost per m3	Energy cost per m3	H2O2 Cost per m3	Energy cost per m3	Total Cost per m3	Total Cost per m3
KA Martelange	0,025	0,0398	0,008	0,0398	0,065	0,048
KA+RÜB Troisvierges	0,023	0,0402	0,006	0,0402	0,063	0,046
KA Rossmillen	0,023	0,0401	0,006	0,0401	0,063	0,046
KA+RÜB Wiltz	0,024	0,0398	0,007	0,0398	0,064	0,047
KA Bettel before Pond	0,027	0,0402	0,011	0,0402	0,067	0,051
KA Bettel after Pond	0,026	0,0402	0,010	0,0402	0,066	0,050
KA+RÜB Pommerloch	0,027	0,0408	0,013	0,0408	0,068	0,054
KA+RÜB Clervaux	0,025	0,0404	0,008	0,0404	0,065	0,048
KA Reisdorf-Wallendorf	0,023	0,0408	0,006	0,0408	0,064	0,047
KA Arsdorf	0,023	0,0404	0,006	0,0404	0,063	0,046
KA Surré	0,023	0,0408	0,006	0,0408	0,064	0,047
KA+RÜB Neuhausen	0,023	0,0486	0,006	0,0486	0,072	0,055
KA Harlange	0,025	0,0399	0,008	0,0399	0,065	0,048
KA Feulen	0,023	0,0398	0,006	0,0398	0,063	0,046
KA Bleesbruck	0,023	0,0399	0,006	0,0399	0,063	0,046
KA Heiderscheidergrund	0,023	0,0399	0,006	0,0399	0,063	0,046

Table 6: Estimation operational cost for the different scenarios

Figure 17 illustrates the estimated H_2O_2 cost per m³ of treated water for each WWTP. The X-axis shows the applied UV fluence (J/m²), while the Y-axis represents the H_2O_2 cost (€/m³). Each bubble corresponds to one WWTP, and its size indicates the H_2O_2 dosage required in the UV/H_2O_2 process.

The results show a clear cost gap between both scenarios. Under best-case conditions, H_2O_2 costs range from approximately 0.005 to 0.012 €/m³, whereas in the worst-case scenarios, they increase sharply to values between 0.022 and 0.029 €/m³.

The higher costs in the worst scenario reflect the effect of increased oxidant dosage, which is directly linked to the higher DIC and TSS levels discussed earlier. These parameters act as •OH scavengers, reducing treatment efficiency and forcing a higher H_2O_2 input to maintain target degradation rates.

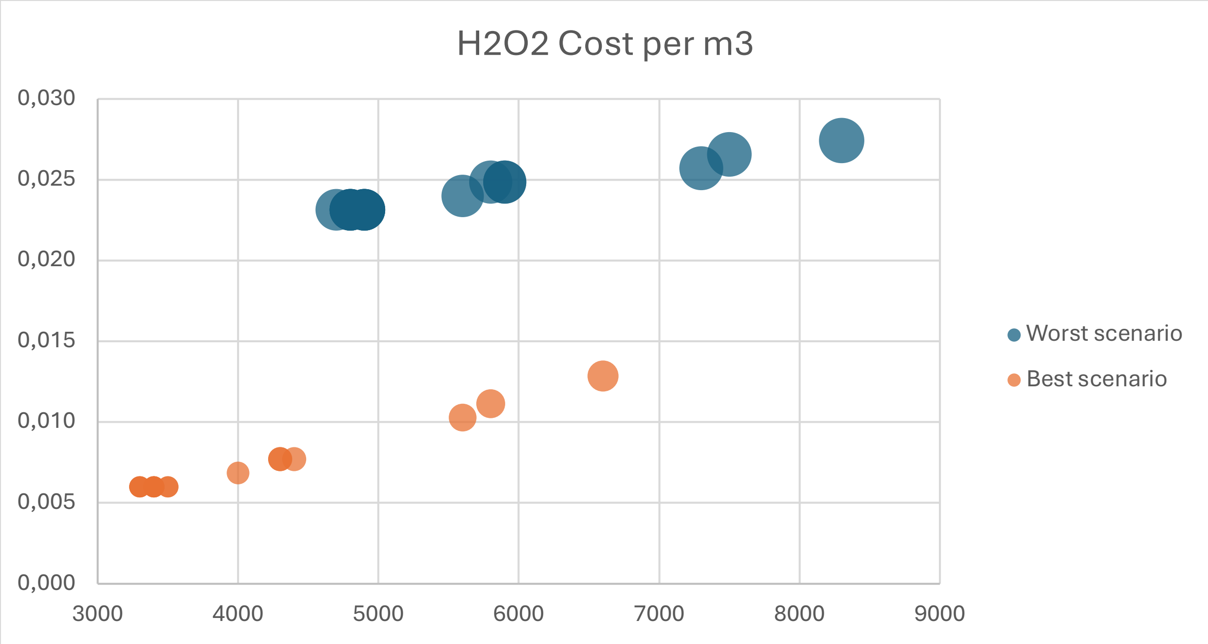

Figure 17: H_2O_2 cost per cubic meter

The data also reveal a general trend. As the required H_2O_2 dosage increases, the treatment cost rises almost linearly, regardless of the plant size or technology. This confirms that chemical consumption is one of the most sensitive parameters in the overall cost structure of AOPs.

In practical terms, maintaining a low and stable oxidant dosage is key to economic feasibility. Optimizing the UV dose and pre-treatment conditions to limit DIC and TSS concentrations can reduce the H_2O_2 demand by up to a factor of three, lowering the total cost from nearly 0.030 €/m³ in the worst case to below 0.010 €/m³ in the best case. This difference illustrates the strong influence of water matrix quality on the financial viability of AOP implementation at the WWTP scale.

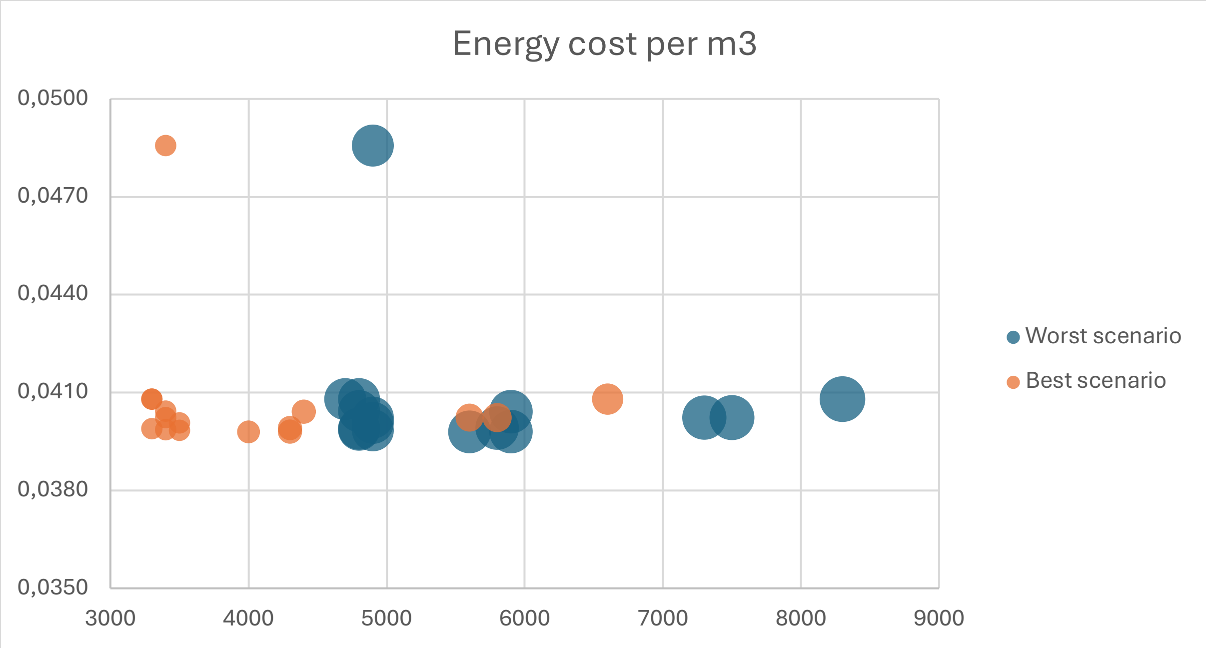

Figure 18: energy cost per cubic meter

Figure 18 presents the estimated energy cost (€/m³) for the UV system across the 15 WWTPs. The X-axis displays the applied UV fluence (J/m²), while the Y-axis represents the specific energy cost (€/m³) associated with UV irradiation. As in the previous figure, each bubble represents one WWTP, with bubble size indicating the H_2O_2 dosage required in the UV/H_2O_2 process.

In general, the energy cost remains relatively stable across most WWTPs, ranging between 0.038 and 0.041 €/m³ in both scenarios. This stability confirms that energy consumption is less affected by water quality than chemical cost, as UV lamp power is primarily determined by flow rate and reactor design. In practice, increasing the H_2O_2 dosage is usually a more efficient way to compensate for poor transmittance than significantly raising UV power, which partly explains the limited variation observed among sites.

However, one plant, Neunhausen, stands out with a notably higher specific energy cost of 0.0486 €/m³, compared to an average of about 0.040 €/m³ for the other sites. This difference is mainly related to its lower T_{10} value (78.7%) and small design flow, which together require maintaining a similar UV intensity as larger plants while treating a smaller volume of water. Although the system would technically require less total power, a minimum UV irradiance must still be maintained to ensure effective photolysis of hydrogen peroxide. This fixed energy demand results in higher specific energy consumption per cubic meter treated.

Overall, the results confirm that while energy costs in the UV/H_2O_2 process are generally stable across technologies, specific costs rise sharply in small-capacity plants, primarily due to the minimum power thresholds required for UV operation relative to flow. These findings emphasize the importance of scale-adapted UV system design and careful balancing between UV fluence and H_2O_2 dosage when implementing AOPs in small WWTPs.

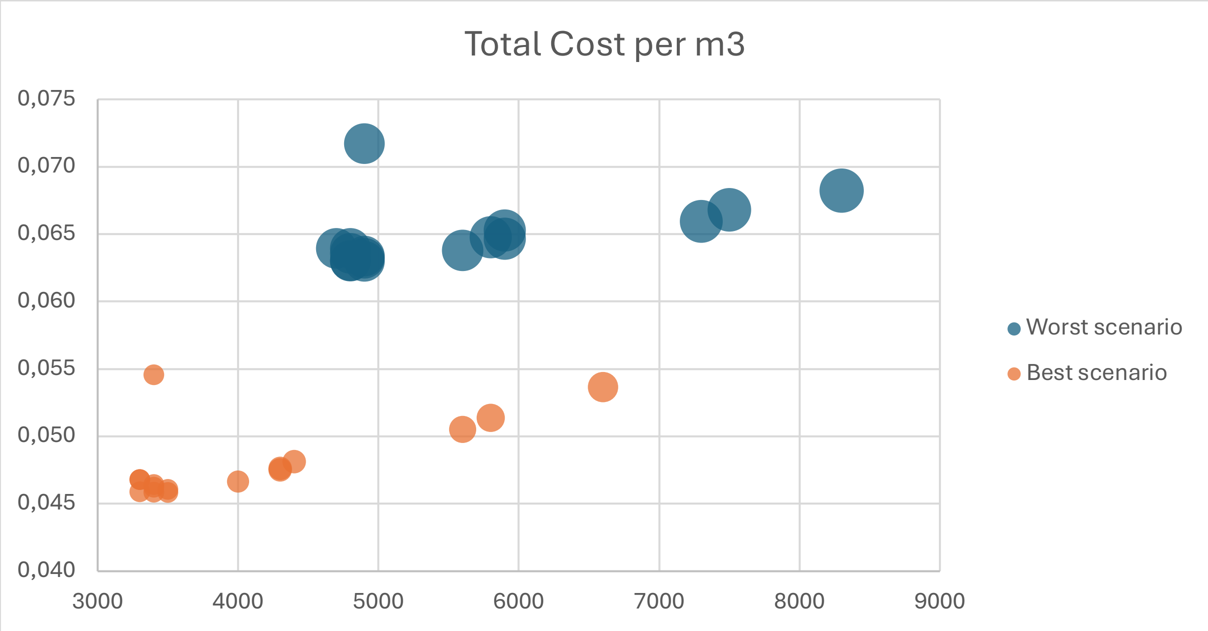

Figure 19: energy and H_2O_2 costs

Figure 19 combines the contribution of both energy demand and H_2O_2 dosage, showing the resulting total cost of UV/H_2O_2 treatment expressed in €/m³ for each of the 15 WWTPs. The X-axis reports the applied UV fluence (J/m²), and the Y-axis indicates the overall operational cost per cubic meter. As before, each bubble represents a WWTP, and the bubble size reflects the H_2O_2 dosage applied in the corresponding scenario.

The results show a clear separation between the two scenarios: in the best cases, total costs range from 0.045 to 0.055 €/m³, while in the worst cases, they increase to between 0.063 and 0.071 €/m³. This corresponds to a difference of about 35–40%, mainly driven by the higher H_2O_2 dosage required under less favorable water quality conditions. These results highlight the sensitivity of the model to input parameters and indicate the need for a more complete approach that includes DIC and other scavenging effects.

Among all plants, Neunhausen again presents the highest total cost (≈0.071 €/m³), which reflects both its higher specific energy consumption and its moderately low T_{10} value (78.7%), requiring a higher combined UV/H_2O_2 dose to maintain performance. In contrast, larger plants such as Heiderscheidergrund (T_{10} = 79.2%) and Feulen (T_{10} = 78.0%) show lower total costs (≈0.046 €/m³), benefiting from stable hydraulic conditions and a greater treatment capacity that distributes the energy demand more efficiently. This strong correlation between T_{10} and total cost demonstrates how effluent clarity directly affects both process efficiency and operating expenses.

Comparing the two cost components, the H_2O_2 dosage accounts for most of the variation, with an estimated increase of up to 200–250% between the best and worst scenarios, while the energy cost changes by less than 5–10%. This confirms that optimizing the oxidant dose is a far more effective lever for cost reduction than modifying the UV energy input. Maintaining high T_{10} and minimizing scavenger levels in the effluent are therefore key to keeping operational costs low and ensuring the economic feasibility of the UV/H_2O_2 process in small and medium-sized WWTPs.

5.6. Discussion of results

The analysis of the fifteen monitored WWTPs provides a comprehensive overview of the key factors influencing the applicability of the UV/H_2O_2 process in small and medium-sized facilities in northern Luxembourg. The parameters assessed during the sampling campaigns, T_{10}, DIC, and TSS, capture complementary aspects of effluent quality that directly determine AOP performance, while the cost analysis translates these technical findings into their practical and economic implications.

- UV Transmittance

The T_{10} values, ranging from 56.3% at Pommerloch to 80.3% at Reisdorf-Wallendorf, revealed a strong variability in T_{10} among the studied WWTPs. Plants based on activated sludge technology showed the widest range, demonstrating that operational and hydraulic factors can differ significantly even within the same configuration. The particularly low transmittance at Pommerloch likely results from hydraulic overloading, driven by the recent expansion of residential and commercial areas around the WWTP. In contrast, Biocos and SBR systems generally achieved higher and more consistent T_{10} values

(≈70–80%), indicating more stable hydraulic performance, although, given the limited number of these plants, this trend should be interpreted as indicative rather than conclusive.

Effluent transmittance above roughly 70% can be considered satisfactory for UV-based treatment, whereas values below 60% suggest higher light attenuation and reduced process efficiency.

- Dissolved Inorganic Carbon

The DIC results further highlight how local geology and catchment characteristics shape effluent composition. Concentrations varied from 11.3 mg/L at Harlange (in the schist-rich Oesling region) to 65.7 mg/L at Bleesbruck (in the carbonate-rich Gutland). Higher DIC values correspond to greater levels of carbonate and bicarbonate species, which act as •OH scavengers and promote calcium carbonate scaling on UV lamp sleeves, reducing process efficiency and increasing maintenance needs.

Based on these results, DIC levels below 20 mg/L imply low interference, 20–50 mg/L indicate moderate scavenging, and values above 50 mg/L represent strong scavenging potential, requiring higher UV or H_2O_2 doses to maintain the desired removal efficiency. Plants like Bleesbruck and Reisdorf-Wallendorf, both exceeding 60 mg/L, would likely need either pre-treatment (e.g., softening or filtration) or operational adaptations to ensure consistent UV/H_2O_2 performance.

- TSS

TSS concentrations, ranging from 1.3 mg/L at Clervaux to 12.3 mg/L at Surré, were generally low but varied across sites. All plants complied with the Urban Wastewater Treatment Directive (91/271/EEC) limits (35–60 mg/L), confirming adequate solids removal. Variations among plants likely stem from differences in sludge settling and clarifier performance, rather than technology type. Elevated TSS values, such as those at Harlange and Bettel (before pond), correspond to lower T_{10} values, suggesting a relationship between solids concentration, light scattering, and hydraulic short-circuiting.

Rain events prior to sampling, especially at smaller plants with limited hydraulic buffering, may also have contributed to temporary increases in suspended solids due to washout in the secondary clarifier. Maintaining low solids content is thus essential not only for compliance but also for optimal T_{10} and •OH utilization.

- Feasibility Assessment Table

To facilitate an integrated interpretation of the results, Table 6 summarizes the overall feasibility of implementing UV/H_2O_2 in each WWTP, based on the measured T_{10}, TSS, and DIC values. Each parameter is qualitatively classified, and an overall feasibility rating is proposed.

WWTP	T_{10}	TSS	DIC	Overall Feasibility
Reisdorf-Wallendorf	+++	++	-	++
Bleesbruck	++	++	-	+
Heiderscheidergrund	+++	++	++	+++
Feulen	++	++	++	++
Clervaux	+	+++	++	++
Surré	++	+	++	+
Pommerloch	-	+	++	-
Bettel (before pond)	+	+	++	+
Bettel (after pond)	+	++	++	+
Wiltz	++	++	++	++
Martelange	++	++	++	++
Troisvierges	++	++	++	++
Rossmillen	++	+++	++	++
Harlange	+	+	+++	+
Neuhausen	++	++	++	++

Table 7: Feasibility Assessment Table

+++ = Very favorable | ++ = Good option | + = Feasible but requires optimization | - = Not favorable

The classification reveals that most plants fall into the "good" to "moderate" feasibility range for implementing UV/H_2O_2. Large and hydraulically stable WWTPs such as Heiderscheidergrund, Feulen, and Wiltz perform best, combining high T_{10}, moderate DIC, and low solids levels, which translates to low operational costs (≈0.045–0.050 €/m³) and consistent oxidation potential.

In contrast, smaller plants like Pommerloch and Surré show less favorable conditions. Their lower T_{10}, higher TSS, and more variable influent compositions increase the need for higher oxidant dosages and frequent maintenance, raising treatment costs to ≈0.065–0.071 €/m³.

These findings highlight a strong link between effluent quality parameters (T_{10}, DIC, TSS), geographical factors, and economic feasibility. The DIC gradient between the carbonate-rich south/east and the schist-dominated north mirrors the pattern of UV/H_2O_2 performance, confirming that local hydrogeology must be factored into design decisions.

Ultimately, the results indicate that UV/H_2O_2 is most viable for medium to large WWTPs with stable effluent quality, moderate carbonate content, and good T_{10}. For smaller or highly variable plants, pre-treatment or alternative AOPs should be considered to balance treatment efficiency with cost-effectiveness.

6. Conclusion and Outlook

This thesis evaluated the applicability of UV/H_2O_2 as a quaternary treatment process for removing MPs in small- and medium-sized WWTPs in northern Luxembourg. The assessment combined field measurements of T_{10}, DIC, and TSS with preliminary cost estimations based on modeled UV and H_2O_2 demand.

The results revealed notable differences in effluent quality among the 15 WWTPs. T_{10} values ranged from 56 to 80 %, indicating that while several plants present favorable optical conditions for UV treatment (e.g., Reisdorf-Wallendorf, Feulen, Heiderscheidergrund), others face limitations linked to hydraulic overload or particulate presence. DIC concentrations varied significantly depending on geological context, with carbonate-rich regions showing stronger scavenging potential and a higher risk of quartz sleeve scaling. TSS concentrations were low overall, confirming good solids removal performance and limited impact on T_{10} under typical conditions.

Cost estimations indicated a potential operating range of approximately 0.045–0.071 €/m³, with H_2O_2 consumption being the primary source of variability. Energy costs remained relatively stable but increased in very small installations due to scale constraints. However, these cost estimates represent an initial modelling step and should not be interpreted as definitive design values, since the approach mainly relied on T_{10} and did not yet incorporate DIC effects, true UV fluence requirements, or full hydraulic behavior.

Despite these limitations, the findings show that UV/H_2O_2 can be technically feasible in several of the evaluated WWTPs. Medium-sized plants with stable flows appear particularly well-suited, while smaller rural facilities may require design adaptations or complementary treatment strategies. The study also highlights how strongly local wastewater characteristics influence the overall performance and financial feasibility of advanced oxidation.

To progress toward real implementation and full compliance with the revised Urban Wastewater Treatment Directive, future work should focus on:

• Incorporating DIC and organic matter interference into UV/H_2O_2 dose optimization
• Pilot-scale validation at representative WWTPs, including MP removal and by-product formation
• More detailed comparisons with other quaternary treatment options (e.g., GAC)
• Assessing seasonal and wet-weather variability, especially in smaller rural systems
• Refining cost models to support practical decision-making for operators and authorities

Personally, conducting this study has made clear to me how challenging, yet necessary, the transition to MP removal will be, especially for decentralized areas like northern Luxembourg. With the right technology choices and site-specific design, even smaller WWTPs can contribute to meeting both environmental protection goals and future regulatory requirements.

By providing this first screening of feasibility and highlighting where further efforts should be directed, this thesis aims to support the ongoing national strategy for sustainable wastewater management and safer surface water quality in Luxembourg.

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8. Annexes

Description of the WWTPs and Sampling Table

The following descriptions of WWTPs are based on information obtained from the official SIDEN website (SIDEN, Les communes membres du SIDEN, 2025) as well as from a detailed data table provided by a SIDEN collaborator. These combined sources include technical specifications, operational capacities, commissioning dates, service areas, and additional relevant characteristics for each WWTP.

- Martelange

The Rombach-Martelange WWTP is a Belgian Luxembourgish biological treatment facility commissioned in 1996. It has a treatment capacity for a p.e. of 7100 and handles a peak flow of 70 L/s, corresponding to an annual treated volume of approximately 571 750 m³. The plant discharges into the Sûre/Sauer River.

The network connected to the plant is of a mixed type, collecting both domestic and stormwater from several Belgian localities (Radelange, Bodange, Martelange, Grumelange) and Luxembourgish villages (Rombach, Wolwelange, and nearby service stations). Four pumping stations, three in Belgium and one in Luxembourg, are integrated into the system. Additional infrastructure includes a stormwater basin in Rombach and a retention channel in Wolwelange, providing hydraulic buffering during wet weather events.

The treatment line comprises pumping, screening, grit and grease removal, stormwater basins, low load activated sludge tanks, and phosphate co-precipitation. Sludge treatment includes thickening in silos, mechanical dewatering with belt filters and polyelectrolyte flocculation, and container loading systems. This setup ensures the biological removal of organic matter and nutrients, supported by robust pre-treatment and sludge handling units. The plant also manages Belgian inflows, which requires binational operational coordination. An overview of the facility layout and main structures is shown in Figure 20, illustrating the various treatment stages and auxiliary installations.


Figure 20: WWTP Martelange

- Arsdorf

The Arsdorf WWTP, located in the commune of Rambrouch, was constructed to serve the villages of Arsdorf and Bilsdorf as well as Heispelt in the commune of Wahl. It replaces the former mechanical treatment plant from 1963, which no longer met the requirements of the current EU Urban Wastewater Treatment Directive. The new facility has a treatment capacity of 1500 p.e., with an inlet flow of 18.5 L/s and an annual treatment volume of approximately 259 242 m³.

The plant uses the BIOCOS® biological treatment process, which combines elements of SBR and continuous flow systems, and includes the addition of lamellas for improved settling. The treatment process allows for the removal of carbonaceous, nitrogenous, and phosphorous compounds.

The infrastructure includes a sludge storage volume of 540 m³, a technical building of 50 m³, and dedicated storage for phosphate precipitants of 6.5 m³. Several stormwater retention basins in the catchment area regulate peak flows before they reach the facility.

Figure 21 shows an aerial view of the Arsdorf WWTP, illustrating the main treatment basins, the technical building, and the surrounding infrastructure.


Figure 21 : WWTP Arsdorf

- Neunhausen

The Neunhausen WWTP, situated in the commune of Esch-sur-Sûre, was commissioned in 1993 and has a treatment capacity of 350 p.e., with a nominal flow rate of 3.5 L/s and an annual treated volume of approximately 56 500 m³. The facility is equipped with BIOCOS® technology combined with a nature-based pilot system, developed in collaboration with the University of Luxembourg.

The treatment line includes an inlet overflow, coarse and fine screening, grit removal, and low load activated sludge tanks. It also integrates a buffer basin, a macrophyte bed for natural tertiary treatment, and a final retention–finishing lagoon to ensure high effluent quality. Sludge generated during the process is stored in a dedicated silo, while a small operations building (“maisonnette”) houses the technical controls.

This combination of BIOCOS® and natural treatment processes aims to optimize nutrient removal and enhance biodiversity in the polishing stages, while providing a robust and low-maintenance solution for small-scale communities.

- Heiderscheidergrund

The Heiderscheidergrund WWTP, located in the commune of Esch-sur-Sûre, is designed as a low-load activated sludge facility. It operates with a seasonal capacity variation, treating a pollutant load of approximately 7330 p.e. in winter and up to 12,000 p.e. during the summer tourist season. The plant has a maximum inflow capacity of 29 L/s in dry weather and 62 L/s during storm events. Its biological reactor (activation basin) has a total volume of 5 620 m^3 split into two lanes, with an oxygen supply of around 1,115 kg O_2/day. The facility also includes secondary clarifiers with a total surface of 276 m^2, sand filtration units, and UV disinfection operating at a wavelength of 254 nm.

Figure 22 shows an overview of the Heiderscheidergrund WWTP layout, including the treatment basins and technical building.

Figure 22: WWTP Heiderscheidergrund

- Feulen

The Feulen WWTP uses the BIOCOS® process configured on three treatment lanes operating in parallel, each designed to optimize both carbon and nutrient removal. In each lane, wastewater first enters an aeration tank where bacterial colonies develop and consume organic pollutants. From there, the flow is recirculated into two alternating sedimentation and mixing basins (SU-Becken), which allow continuous treatment while separating sludge from treated water. The treated effluent is discharged into the natural environment, while stabilized sludge is stored in silos before on-site dewatering. The plant also features partial denitrification, phosphate co-precipitation, sand filtration, fine screening, grit and grease removal, as well as air deodorization systems. With a treatment capacity of 9000 p.e. and a design flow of 64 L/s (750 000 m^3/year), this facility serves both industrial and rural areas, making it one of the region's key WWTPs. Figure 23 shows an overview of the Feulen WWTP layout and infrastructure.

Figure 23: WWTP Feulen

- Surré

The Surré WWTP is in the locality of Surré, within the municipality of Boulaide. It is a small-scale rural installation with a treatment capacity of 450 p.e. The plant operates a SBR system, suitable for small communities with variable inflows. With a nominal capacity of 5 L/s and an annual treated volume of approximately 95 150 m³, the facility is designed to handle domestic wastewater from the surrounding villages.

- Harlange

The Harlange WWTP, located in the commune of Lac de la Haute-Sûre, was commissioned in 1985. It has a treatment capacity of 2500 p.e. and a nominal flow rate of 46 L/s, corresponding to an annual treated volume of approximately 534 145 m³. The process in use is a low load activated sludge system, well-suited to the rural character of the area served.

The facilities include a screening system, an overflow structure, grit removal, two sludge silos, as well as a small technical building and a medium-voltage station. This configuration ensures effective biological treatment while remaining compact and adapted to the needs of the local community.

- Pommerloch

The Pommerloch WWTP, located in the locality of Pommerloch within the commune of Winseler, was built in 1995. It has a treatment capacity of 1500 p.e., corresponding to an annual flow of 420 000 m³/year and an average hydraulic load of 20 L/s. The plant operates with activated sludge technology and is equipped with several key components: an overflow system, a mixed water overflow basin, a stormwater basin, mechanical screening, grit removal, low-load activated sludge tanks, two finishing-retention lagoons, a regional sludge silo, an industrial water installation, and an operator building.

- Wiltz

The Wiltz WWTP, located in the commune of Wiltz, was originally built in 1975 and designed to treat a biological pollution load equivalent to 16 500 p.e. The plant serves the towns of Wiltz and Niederwiltz, as well as the localities of Weidingen and Roullingen, with planned connections to the villages of Noertrange and Winseler. The collection network, equipped with four stormwater basins, is of mixed type and operates entirely by gravity, except for the Roullingen connection.

The facility underwent a five-year modernization program, culminating in its official reopening on 22 September 2017, together with the Weidingen stormwater basin. The treatment process includes flow regulation, screening, grit removal, primary settling, medium load activated sludge treatment, sludge mineralization, and sludge drying beds. The plant also houses a workshop building, a medium-voltage station, and on-site management services.

As shown in Figure 24, the layout of the Wiltz WWTP is integrated within a wooded area, with distinct sections for preliminary, primary, and biological treatment.

Figure 24: WWTP Wiltz

- Bleesbruck

The Bleesbruck WWTP is the largest wastewater treatment facility in the Siden network, with a treatment capacity of 130 000 p.e. and a maximum hydraulic load of 375 L/s. It serves a mixed catchment composed of both urban and industrial effluents. The treatment line includes coarse and fine screening, grit and grease removal, primary sedimentation, classical activated sludge tanks with longitudinal clarifiers, and an advanced sludge treatment section comprising thickening, digestion, and dewatering by centrifugation. Biogas produced from sludge digestion is valorized via cogeneration, contributing to the plant's energy self-sufficiency.

The facility underwent a major modernization in 2009–2017, which included the construction of new covered grit and grease removal units, an upgraded pumping station, and provision for a potential future quaternary treatment stage.

An aerial view of the Bleesbruck WWTP is shown in Figure 25, highlighting the layout of the main treatment units and the extensive on-site infrastructure.

Figure 25: WWTP Bleesbruck

- Bettel

The Bettel WWTP, located along the Our River and serving a partially cross-border catchment area, was constructed in 2001 to treat a pollution load equivalent to 9000 p.e. The collection network is of a mixed type, serving the Luxembourgish villages of Fouhren and Bettel, as well as the German localities of Roth and Gentingen. The facility is equipped with four pumping stations and three retention pipelines. The treatment process includes coarse screening, grit removal, oil removal, two-stage sedimentation, biodiscs with Dortmund decanter, infiltration lagoon, odour control filter, industrial water installation, and a workshop building. The plant operates with a nominal capacity of 60 L/s and is representative of small-scale rural treatment plants employing compact biological treatment solutions.

Figure 26 shows a layout of the Bettel WWTP, highlighting the location of the main process units.

Figure 26: WWTP Bettel

- Reisdorf-Wallendorf

The Reisdorf–Wallendorf WWTP, located in the commune of Reisdorf, was constructed in 2012 with a treatment capacity of 4300 p.e. The plant operates using a low load activated sludge process and includes additional treatment stages such as screening, grit removal, and sludge lagooning. The facility also features a flow overflow structure and is complemented by a small operations building.

- Rossmillen

The Rossmillen-Weiswampach WWTP, constructed in 2003, has a treatment capacity of 5000 p.e. and replaced the former Weiswampach plant (2000 p.e., built in 1982) to meet the needs of the commune's urban expansion. The mixed-type collection network serves Weiswampach as well as the localities of Binsfeld, Breidfeld, Holler, Massen, and Wemperhardt, and includes five pumping stations and four retention pipelines. The treatment line comprises coarse screening, grit removal and classification, oil and grease removal, low load activated sludge, phosphate co-precipitation, sludge reception and thickening, mechanical dewatering with polymer flocculation, and odour control through a compost filter.

Figure 27: WWTP Rossmillen

- Clervaux

The Clervaux WWTP, originally built in 1972 with a treatment capacity of 1500 p.e., underwent an upgrade in 1987 to reach 4500 p.e. Due to the expansion of the mixed sewer network serving Clervaux, Eselborn, the Lentzweiler industrial zone, Mecher, and part of Reuler, the construction of a new plant was launched in 2019. The modern facility is designed for a load of 9700 p.e. and includes equipment for screening, grit removal, and low/medium-load activated sludge treatment, as well as an aerobic sludge stabilization tank and a sludge silo. Additional infrastructure, such as stormwater tanks and a pumping station, complements the network, with most inflows arriving by gravity.

- Troisvierges

The Troisvierges WWTP has a treatment capacity of 9000 p.e. It treats not only the wastewater from the localities of Troisvierges and Biwisch but also from the villages of Drinklange, Wilwerdange, Goedange, Huldange, and Schmiede, with part of the treated water discharged in Ulflingen. Construction of the plant began in June 2017, and it was commissioned in 2022. The facility has a nominal flow capacity of 60 L/s and serves both industrial and rural areas.

Figure 28 : WWTP Troisvierges

	Wastewater Treatment Plant	Sampling No.	Date	Time	Weather Condition	Transmittance (%)	TOC (mg/L)	TC (mg/L)	IC (mg/L)	TS (mg/L)
1	**KA Martelange**	1	30/04/2025	7.08am	Dry	73	4,721	14,33	9,614	/
		2	04/06/2025	8.10am	Dry	69,2	4,312	27,39	23,08	4,00
		3	21/07/2025	8.01am	Dry	66,6	7,457	22,67	15,21	8,00
2	**KA+RÜB Troisvierges**	1	29/04/2025	8.11am	Dry	84,8	4,056	32,02	27,97	/
		2	03/06/2025	8.43am	Dry	79,3	1,319	31,87	30,55	2,0
		3	22/07/2025	8.23am	Dry	72,3	3,858	35,30	31,44	10,00
3	**KA Rossmillen**	1	29/04/2025	7.53am	Dry	78	2,116	31,38	29,26	/
		2	03/06/2025	8.13am	Dry	72,6	3,243	31,94	28,70	0,25
		3	22/07/2025	8.06am	Dry	71,6	6,040	38,12	32,06	3,5
4	**KA+RÜB Wiltz**	1	30/04/2025	11.05am	Dry	79,4	0,7678	37,03	36,26	/
		2	04/06/2025	11.10am	Dry	71,6	0,2479	48,28	48,04	2,5
		3	21/07/2025	11.16am	Dry	66,0	38,55	39,21	0,6546	6,00
5	**KA Bettel before Pond**	1	06/05/2025	9.45am	Dry	60,9	/	/	/	/
		2	03/06/2025	11.24am	Dry	59,3	8,407	38,94	30,53	8,5
		3	22/07/2025	11.01am	Dry	59,9	0,2306	0,4409	0,2102	5,3
	KA Bettel after Pond	1	06/05/2025	9.45am	Dry	61,8	7,482	41,80	34,32	/
		2	03/06/2025	11.24am	Dry	60,1	8,324	40,93	32,60	4,75
		3	22/07/2025	11.01am	Dry	61,5	10,15	28,12	17,96	1,3
6	**KA+RÜB Pommerloch**	1	30/04/2025	10.43am	Dry	58	10,29	34,12	23,83	/
		2	04/06/2025	10.44am	Dry	53,8	10,90	31,12	20,22	5,00
		3	21/07/2025	10.45am	Dry	57,1	8,844	22,80	13,96	6,6
7	**KA+RÜB Clervaux**	1	29/04/2025	8.42am	Dry	76,3	4,849	30,99	26,14	/
		2	03/06/2025	9.33am	Dry	66,6	1,440	40,84	39,40	1,11
		3	22/07/2025	8.49am	Dry	65,6	5,192	46,31	41,12	1,5
8	**KA Reisdorf-Wallendorf**	1	06/05/2025	9.14am	Dry	80,4	3,162	76,32	73,16	/
		2	03/06/2025	10.53am	Dry	79,4	5,175	71,93	66,76	2,25
		3	22/07/2025	10.30am	Dry	81,2	/	43,54	43,54	3,5
9	**KA Arsdorf**	1	30/04/2025	7.27am	Dry	83,7	/	33,34	33,34	/

		2	04/06/2025	8.29am	Dry	79,7	1,688	29,33	27,64	5,75
		3	21/07/2025	8.27am	Dry	74,4	4,492	25,09	20,60	3,3
10	**KA Surré**	1	30/04/2025	10.02am	Dry	81,6	0,5540	35,26	34,71	/
		2	04/06/2025	10.11am	Dry	79	2,579	29,49	26,91	8,5
		3	21/07/2025	10.23am	Dry	70	7,230	24,77	17,54	16,00
11	**KA+RÜB Neuhausen**	1	30/04/2025	7.51am	Dry	82,9	/	35,26	35,26	/
		2	04/06/2025	8.42am	Dry	75,2	/	43,31	45,31	2,75
		3	21/07/2025	8.39am	Dry	77,9	3,169	31,79	28,62	1,3
12	**KA Harlange**	1	30/04/2025	10.17am	Dry	74,9	6,395	19,99	13,60	/
		2	04/06/2025	10.22am	Dry	69,2	5,590	15,96	10,37	14,00
		3	21/07/2025	10.04am	Dry	67	6,592	16,43	9,834	2,00
13	**KA Feulen**	1	30/04/2025	8.46am	Dry	82,5	/	40,23	40,23	/
		2	04/06/2025	9.10am	Dry	76	/	41,03	41,03	1,5
		3	21/07/2025	9.09am	Dry	75,5	4,032	32,22	28,19	6,6
14	**KA Bleesbruck**	1	06/05/2025	8.54am	Dry	76,8	4,824	80,24	75,42	/
		2	03/06/2025	10.36am	Dry	75,8	/	65,58	65,58	2,25
		3	22/07/2025	10.13am	Dry	78,3	1,770	57,20	55,43	5,00
15	**KA Heiderscheidergrund**	1	30/04/2025	9.30am	Dry	81,3	1,464	6,667	5,203	/
		2	04/06/2025	9.32am	Dry	80,5	1,947	29,43	27,48	2,25
		3	21/07/2025	9.33am	Dry	75,7	5,091	31,26	26,17	8,00