Carbon footprint of chlorination and photocatalytic tertiary wastewater treatments

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Abstract. This study depicts a comparative carbon footprint analysis of two tertiary wastewater treatment methods: chlorination and photocatalytic. It integrates data from an extensive literature review and an on-site investigation conducted at the Aqualia plant in Spain. The analysis employed a Life Cycle Assessment (LCA) methodology using SimaPro software to assess the carbon footprint of each treatment method. Data was collected from various literature sources and the Aqualia plant. Results indicate that the chlorination process exhibits a lower carbon footprint than the photocatalytic process. Notably, the electricity requirements of the photocatalytic treatment contribute significantly to its higher carbon emissions. The literature review and the data collected from the Aqualia plant consistently support the finding that the energy-intensive nature of the photocatalytic process leads to more significant carbon emissions. Despite the higher treatment efficiency of the photocatalytic process, the analysis reveals that the chlorination process remains a more environmentally favorable choice regarding carbon footprint. The substantial electricity demand of the photocatalytic process offsets its efficiency benefits, resulting in higher carbon emissions. In conclusion, while photocatalytic treatment demonstrates superior wastewater treatment efficiency, a holistic consideration of environmental impacts is crucial. These insights provide valuable guidance for stakeholders in the wastewater treatment industry, supporting adopting sustainable practices that prioritize reducing carbon emissions.

1 Introduction

Climate change is a pressing global issue that threatens the delicate balance of our planet's ecosystems. The burning of fossil fuels, deforestation, and industrial activities that emit greenhouse gases into the atmosphere are the main causes of the world's unprecedented climatic change **[1]**. Rising sea levels, a rise in the frequency and severity of natural catastrophes like hurricanes, droughts, and wildfires, a decline in biodiversity, and harm to agricultural systems are just a few of the numerous effects of climate change on the environment. These problems represent severe dangers to human health, safety, and economic stability, in addition to being a threat to the environment. By adopting sustainable behaviors, lowering carbon emissions, and investing in renewable energy sources, individuals, companies, and governments must work to combat climate change. Multiple assessment methods can be used to identify the effects on the environment of a specific process or product, such as life cycle assessment (LCA).

LCA is a procedure used to assess the environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to disposal. LCA aims to identify the ecological hotspots and potential impacts of a product or service and provide guidance for improvement (Figure 1). LCA is a comprehensive and quantitative approach considering various environmental indicators such as greenhouse gas emissions, water consumption, and land use **[2, 3]**. Moreover, LCA consists of four main phases: 1. Goal and Scope Definition, 2. Inventory Analysis, 3. Impact Assessment, and 4. Interpretation (Figure 2).

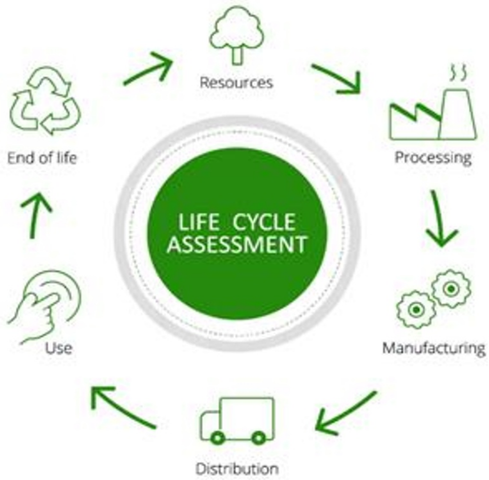

Fig. 1. Life cycle assessment Stages [4]

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A “carbon footprint” focuses exclusively on the carbon emissions of a product or service throughout its life cycle. The carbon footprint refers to all direct and indirect greenhouse gas emissions connected with a service or product, such as those resulting from using energy, transportation, and waste disposal.

A carbon footprint is measured in units of CO_2 equivalent (CO_{2eq}), which assesses the impact of greenhouse gases on the atmosphere. The CO_{2eq} of an activity is determined by multiplying the amount of GHG released by the global warming potential (GWP) of that gas. The GWP measures how much heat a gas traps in the atmosphere compared to the reference substance for climate change, CO_2. From this perspective, reducing the carbon footprint is essential and could be achieved in multiple ways, such as reducing waste from sources, reducing energy consumption, supporting sustainable businesses, and recycling.

A wastewater treatment plant uses physical, biological, and chemical processes to remove pollutants from wastewater before the latter is discharged into the environment. A typical wastewater treatment plant involves three stages: primary, secondary, and tertiary treatments **[5]**. The primary treatment process typically consists of physical processes, including screening, grit removal, and primary sludge sedimentation. The secondary treatment is a biological treatment of the dissolved and suspended organic matter and nutrients (nitrogen and phosphorous) that were not removed during primary treatment using microorganisms such as bacteria, fungi, and protozoa **[6]**. Tertiary treatment is the ultimate removal of any remaining pollutants to produce a high-quality effluent that is safe to discharge into the environment or reuse for beneficial purposes **[7]**. Multiple methods might be used in tertiary treatment, such as chlorination, UV, and ozonation. These methods involve the use of chemical oxidants, such as hydrogen peroxide, ozone, or ultraviolet radiation, to break down microorganisms and persistent organic compounds that may be present in the treated wastewater. In addition, tertiary treatment is not always necessary or required, but it is often used in wastewater treatment plants that discharge treated wastewater into sensitive environments, such as rivers, lakes, or coastal areas, or that reuse treated wastewater for non-potable purposes, such as irrigation, industrial processes, or groundwater recharge. This study is dedicated to chlorination and photocatalytic treatments widely used as tertiary treatments **[8]**.

The carbon footprint of a wastewater treatment plant can be divided into two main components: direct emissions and indirect emissions. The direct emissions are usually due to the combustion of fossil fuels for power generation, while the indirect emissions are generated outside the wastewater treatment plant and are equally important for the plant’s operation **[9]**.

2 Methodology

The schematic below (Figure 2) shows the four methodological steps involved in this study, i.e., goal and scope, inventory analysis, impact assessment, and interpretation.

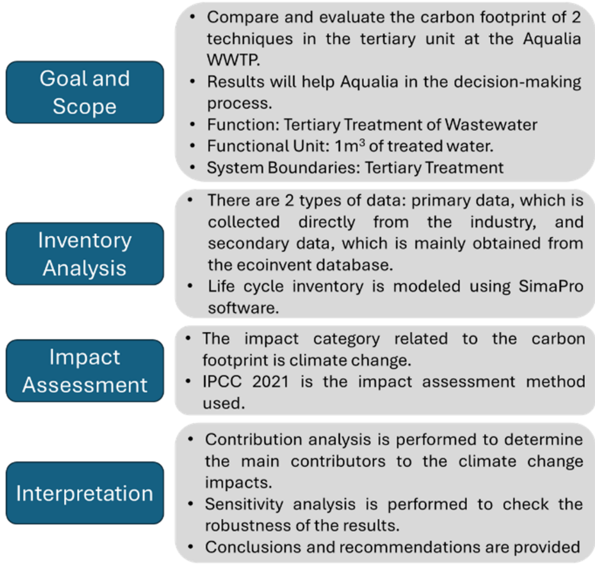

Fig. 2. Methodology Steps.

2.1. Goal and Scope

This comparative study aims to investigate the carbon footprint of organic micropollutants in tertiary treatments in WWTP for two different wastewater treatment technologies: chlorination and photocatalytic treatment (UV). In particular, the aim is to identify the carbon footprint so that the industry can subsequently reduce it.

In LCA, the functional unit quantifies the product’s performance to compare different alternatives. In this study, the functional unit is 1 m^3 of wastewater treated by tertiary treatment. The reference flow refers to the number of products required to fulfill the functional unit. It is used to calculate the system inputs and outputs. Therefore, the reference flow is 1 m^3 of treated wastewater.

The product system is the collection of unit processes connected to product flows. The system boundaries (Figure 3) define the unit processes that will be included in the study in an iterative way. Indeed, while performing the survey, processes might be included or excluded based on the data availability. In this study, the system boundaries will specifically cover the wastewater treatment plant and the tertiary treatment unit.

More to the point, the steps depicted in Figure 3 represent the path of the wastewater effluent once it enters the treatment plant, passing by the tertiary treatment and ending with reusing the treated effluent.

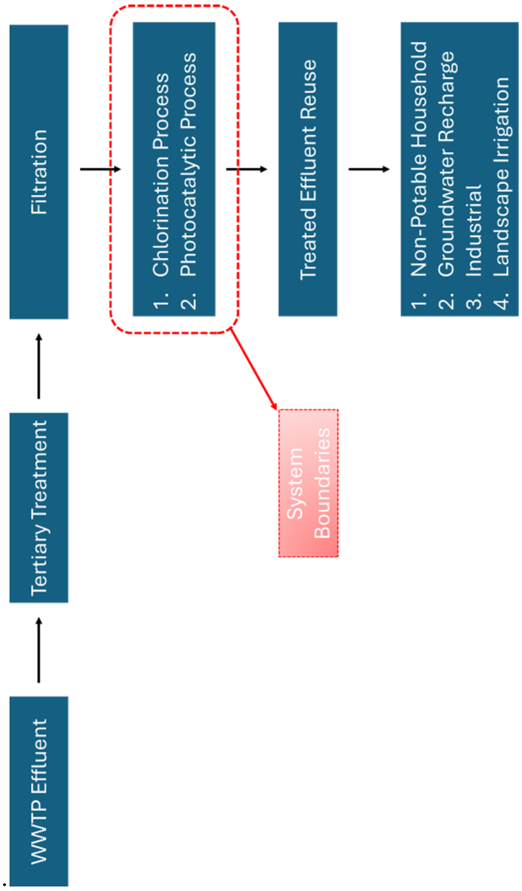

Fig. 3. System Boundaries for LCA of Tertiary Unit

2.2 Life Cycle Inventory (LCI)

Different data should be collected first to perform the carbon footprint study. In particular, it is necessary to differentiate between Foreground and Background data. Foreground data is specific to the product used and related directly to the source. Background data is not directly specific to the product being studied but is still relevant to the study. In the current work, data used to model the unit process is directly provided by Aqualia and displayed in the table below. For confidentiality reasons, the electricity consumption of the tertiary treatment was extracted from the literature.

Table 1. Composition of The Effluent Entering The Tertiary Unit.

	Input	Unit	Year 22
Inlet total flow rate	Flow Rate	m^3/day	51860
Tertiary input	Suspended Solids, unspecified	kg/m^3	0.0052
	Chemical Oxygen Demand	kg/m^3	0.0240
	Biological Oxygen Demand	kg/m^3	0.0040
	Total Nitrogen	kg/m^3	0.0094
	Total Phosphorus	kg/m^3	0.0008
	NH_4^+-N	kg/m^3	0.0038
	NO_3^--N	kg/m^3	0.00367
	Hypochlorite	Kg/m^3	0.28627

2.3 Carbon Footprint Assessment

In an LCA study, the environmental issues of concern are represented by an impact category. The impact category describes the analyzed process system or the impacts caused by the process. During Life Cycle Impact Assessment (LCIA), the releases contributing to the same environmental issue are grouped into a single impact category assigned with one single unit. The inputs and outputs from and to the environment are estimated as potential environmental impacts during LCIA. Thus, different impact assessment techniques may result in various results. IPCC 2021 will be used for the current carbon footprint assessment to assess the Carbon footprint of the WWTP **[10]**.

3 Results and Discussion

3.1. Chlorination process

The results of the carbon footprint (CF) assessment for the chlorination process in the tertiary unit of the WWTP are depicted in Figure 4. The most significant impact in terms of greenhouse gas emissions is attributed to the electricity generated by electricity, which accounts for 69.3% of the carbon footprint, with carbon dioxide being the primary GHG emitted (0.0125 kg CO_{2eq}). Following this, the electricity generated by the biogas engine contributes to 29.7% of the CF emissions. On the other hand, the lowest percentage of emissions, amounting to 3.12%, is associated with electricity generated by solar panels.

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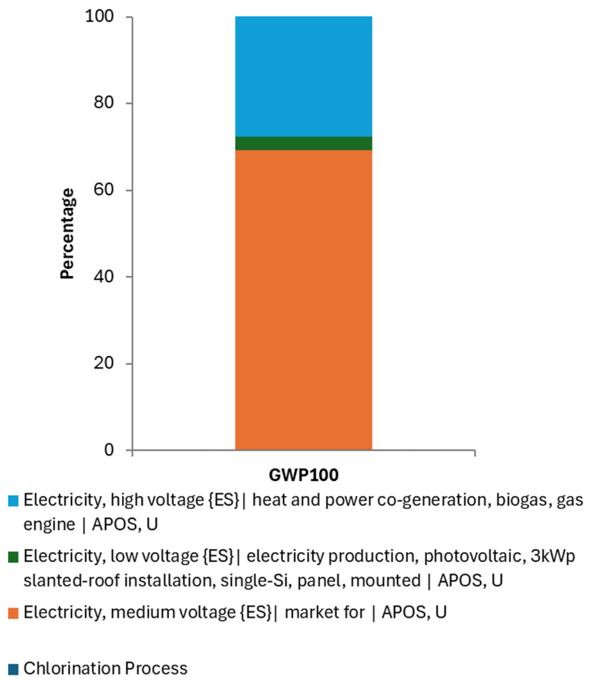

Fig. 4. Carbon Footprint of The Chlorination Process

3.2. Photocatalytic process

Figure 5 illustrates the outcomes of the carbon footprint assessment for the photocatalytic process in the tertiary unit of the WWTP. Electricity is the primary factor influencing greenhouse gas emissions, contributing to 78.9% of the carbon footprint. Subsequently, the electricity generated by the biogas gas engine accounts for 11.6% of the CF emissions. In contrast, the electricity generated by solar panels has a minor contribution equivalent9.5% of the total emissions.

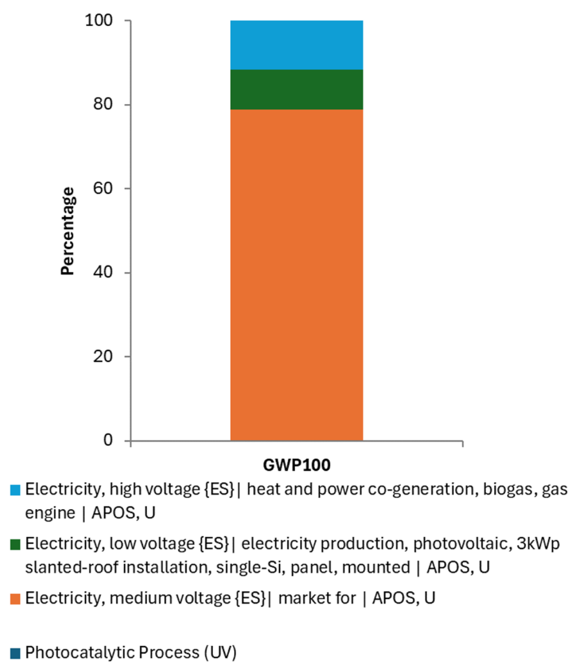

Fig. 5. Carbon Footprint of The Photocatalytic Process

3.3. Comparison

When examining the carbon footprints of the chlorination and photocatalytic processes in the tertiary unit of the WWTP, evident differences become noticeable. Chlorination primarily emits greenhouse gases from generators (69.3%), while the photocatalytic process emphasizes generator-generated electricity (78.9%). Biogas engines contribute 29.7% in chlorination and 11.6% in photocatalysis. Solar panels have a minor role in chlorination (3.12%) but a slightly higher contribution in photocatalysis (9.5%). These differences show the varying environmental impacts of the two methods.

The graph in Figure 6 illustrates the overall comparison of carbon footprint between the two technologies mentioned above used in the tertiary unit in the WWTP.

The photocatalytic process demonstrates a higher carbon footprint due to its greater reliance on electricity. Specifically, the photocatalytic process consumes 0.394 kilowatt-hours (kWh) of electricity, while the chlorination process has a significantly lower consumption of 0.063 kWh. This discrepancy in electricity consumption suggests that the photocatalytic process relies more heavily on electricity, mainly from generators, leading to more elevated GHG emissions. The generation of electricity, often derived from fossil fuels, contributes significantly to the carbon footprint.

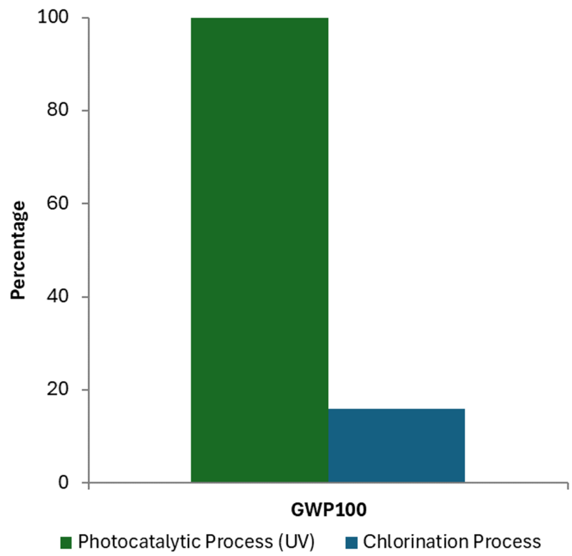

Fig. 6. Comparing the Carbon Footprint of The Chlorination Process with the Photocatalytic Process

3.4. Sensitivity

Sensitivity analysis is crucial in LCA. Its main objective is to identify the input factors that have the most significant impact on LCA outcomes. Various approaches to conducting sensitivity analysis in LCA include single-way, multi-way, and global sensitivity analysis. This research employs the one-way sensitivity analysis method on a new photocatalytic process that relies entirely on solar energy compared to the chlorination process. This method is commonly used in LCA studies due to its simplicity and widespread adoption. It allows for a focused examination of the sensitivity of LCA results to individual input parameters.

In this case, a modification for the photocatalytic process was applied. Using SimaPro, a modification to the sources of electricity was applied by moving all the sources into solar energy sources. An apparent decrease in the difference in emission between the two processes was observed. In this case, the photocatalytic treatment emits approximately more than two times more GHGs than the chlorination process. This is a notable difference from the original scenario, which had five times more emissions than chlorination. However, chlorination still emits fewer GHGs despite this change than the photocatalytic treatment. This is mainly due to the extensive reliance of the photocatalytic treatment on electricity, which is not the case for chlorination.

The results of this study are in line with the ones reported in the literature—for instance, the LCA conducted by Tsangas, M., et. Al. in 2023, to evaluate the environmental impacts of a typical activated sludge plant in Greece, revealed that the energy produced from the biogas in Scenario II (0.2952 KWh/FU) was much higher than the other two scenarios (0.048 KWh/FU for baseline, 0.092 KWh/FU for Scenario I) **[11]**.

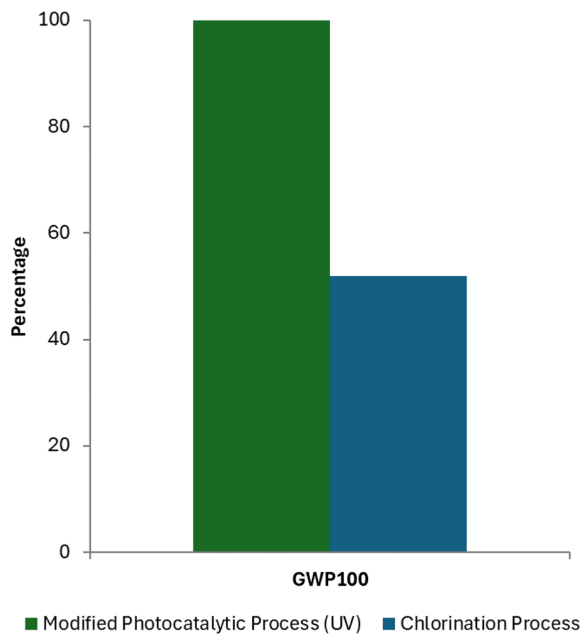

Fig. 7. Comparing the Carbon Footprint of The Chlorination Process with the Modified Photocatalytic Process

4 Conclusion

These findings highlight the importance of considering the overall environmental impacts when evaluating wastewater treatment methods. While photocatalytic treatment demonstrated superior efficiency in wastewater treatment, the analysis revealed that the chlorination process remained a more environmentally friendly option due to its lower carbon footprint. Moreover, the implications of these findings are significant for decision-makers in the wastewater treatment industry. By prioritizing the reduction of carbon emissions, they can select treatment methods that align with sustainability objectives. Moreover, this study provides valuable insights for developing future wastewater treatment strategies, emphasizing the need to balance efficiency and environmental impact.

It is important to note that this study focused specifically on comparing carbon footprints between chlorination and photocatalytic treatment. Further research could explore additional environmental indicators and incorporate broader sustainability aspects such as water usage, chemical usage, and waste generation to evaluate these treatment methods comprehensively.

Overall, this study contributes to understanding the environmental performance of chlorination and photocatalytic treatment in terms of their carbon footprints. The findings underscore the significance of conducting carbon footprint assessments and considering energy-intensive processes when evaluating wastewater treatment options. The wastewater treatment industry can make substantial progress toward environmental stewardship and resource conservation by implementing sustainable practices that minimize carbon emissions.

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