



Environmental impacts and economic assessment of a large-scale pilot plant for micropollutants removal: Granular activated carbon vs. coupled advanced oxidation process-granular activated carbon treatments

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ABSTRACT

Water scarcity requires efficient use, but also protection of surface water quality. Micropollutants are poorly removed in conventional wastewater treatment plants (WWTPs), necessitating the implementation of quaternary treatments to avoid their discharge. This study evaluates the environmental impacts and the cost of six treatment scenarios in a large-scale pilot plant (4–19 m³ d⁻¹) at Heiderscheidergrund WWTP (Luxembourg): stand-alone granular activated carbon (GAC) (fresh (F) and regenerated (R)), photo-Fenton (PF)+GAC (F and R), and UV/H₂O₂+GAC (F and R). The environmental impacts were evaluated using Life Cycle Assessment (LCA), which identified five principal impacts: global warming (GHG), photochemical ozone formation (POCP), human toxicity - cancer effects (HTP-C), resource depletion - energy carriers (E-RD), and water resource depletion (W-RD) as the most affected categories. The overall ranking of impacts across scenarios was: PF+FGAC > PF+RGAC > UV/H₂O₂+FGAC > UV/H₂O₂+RGAC > FGAC > RGAC. Electricity was the main contributor in almost all cases, whereas chemical reagents were more relevant in toxicity-related impacts. Sensitivity analysis revealed that replacing the current electric mix with 100 % renewables reduced GHG by up to 72 %, whereas 100 % fossil energy increased it by up to 173 %. For GAC, W-RD was particularly sensitive to the activation method, with alternative datasets increased up to 473 % in the fresh GAC scenario. Cost assessment showed stand-alone GAC as the cheapest option and coupled AOP-GAC systems incurring higher costs, mainly from energy. This integrated evaluation provided quantitative evidence to support the selection of sustainable quaternary treatments in line with European Union water resilience objectives.

Abbreviations

AOP	Advanced Oxidation Processes
AP	Acidification of Terrestrial and Freshwater
CAPEX	Capital Expenditure
CRF	Capital Recovery Factor
E-RD	Resource Use, Energy Carriers
EU	European Union
F GAC	Fresh GAC stand-alone
F-EP	Eutrophication Freshwater
FETP	Ecotoxicity Freshwater
GAC	Granular Activated Carbon
GHG	Global Warming

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HTP-C	Cancer Human Health Effects
HTP-NC	Non-Cancer Human Health Effects
IRP	Ionising radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
M-EP	Eutrophication Marine
M-RD	Resource Use, Mineral and Metals
ODP	Ozonation depletion
OPEX	Operational Expenditure
PE	Population equivalent

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PF + F GAC	Photo-Fenton coupled with fresh GAC
PF + R GAC	Photo-Fenton coupled with regenerated GAC
PMF	Respiratory Inorganics
POCP	Photochemical Ozone Formation
R GAC	Regenerated GAC stand-alone
T-EP	Eutrophication Terrestrial
UV/H ₂ O ₂ + F GAC	UV/H ₂ O ₂ coupled with fresh GAC
UV/H ₂ O ₂ + R GAC	UV/H ₂ O ₂ coupled with regenerated GAC
W-RD	Water Resource Depletion (Water Scarcity)
WWTP	Wastewater Treatment Plant

1. Introduction

Water pollution has a direct impact on both human health and environmental integrity, particularly when it compromises drinking water sources and sensitive ecosystems. Urgent actions are therefore required to address contaminants that pose a risk to natural water bodies, ensuring their good quality status, as underscored by the European Water Resilience Strategy [1].

Previously, the revised European Union (EU) Urban Wastewater Treatment Directive [2] already introduced new measures aimed at improving water quality. These measurements include stricter discharge limits (concentration and removal rates) on the wastewater treatment plants (WWTPs) for nitrogen and phosphorus, or the implementation of quaternary treatment on high population equivalent (PE) WWTPs to remove micropollutants. The objective of the Directive was not only to improve water quality, but also to minimise the environmental impacts of the treatment process, introducing the energy neutrality target in WWTPs. This initiative will contribute to restore water quality. In parallel, the European Water Resilience Strategy reinforces this objective while also positioning water resilience as both an environmental priority and a business opportunity for EU industry [1].

Within this context, micropollutants represent one of the biggest challenges for water pollution reduction as they are poorly removed via conventional biological treatments at WWTPs. Micropollutants are anthropogenic organic substances such as pharmaceuticals, pesticides, and personal care products, which are present in very low concentrations but are highly persistent and recalcitrant. Their continuous release into aquatic ecosystems has been associated with toxicological effects, bioaccumulation, and potential risks for human health through the water cycle [3–5]. Addressing the problem of micropollutants is therefore essential not only for environmental protection but also for safeguarding drinking water resources and achieving the goals of the EU strategies.

Several technologies have been applied as quaternary treatments for micropollutant removal with promising results, including advanced oxidation processes (AOPs) [6], ozonation [7], membranes [8], and granular activated carbon (GAC) [9]. More recently, hybrid and integrated systems have been proposed to enhance micropollutant removal efficiency while minimising secondary environmental impacts, such as nanofiltration and AOP [10] or ozone and GAC. Scaling up such innovative treatment trains is crucial to meet regulatory requirements and guarantee a good water quality. It also supports the competitiveness of the European water sector while advancing the broader goals of EU water resilience [1].

Among the available treatment options, AOPs have been frequently reported as successful technologies for WWTPs' effluent purification. The use of photocatalytic AOPs avoids several limitations associated with other technologies. For example, ozonation reacts very selectively with carbon-carbon multiple bonds [11] and membranes produce a concentrated and highly polluted stream [12]. Moreover, it enhances overall treatment efficiency compared to non-photolytic AOPs, providing a more robust and adaptable alternative for full-scale implementation [13]. Within this group, the photo-Fenton process has been

identified as a promising alternative due to the high production of hydroxyl radicals, enabling faster micropollutant removal kinetics [14]. The photo-Fenton process is typically carried out at acidic pH, but several studies have reported successful operation at near-neutral pH using chelating agents, achieving over 80 % removal [15]. This makes homogeneous photo-Fenton particularly attractive for WWTP applications, avoiding the need for pH adjustment. In contrast, UV/H₂O₂ generates fewer hydroxyl radicals and therefore exhibits slower reaction kinetics, but it remains an attractive alternative since it avoids the use of iron [16] and the pH issue [17]. Although UV/H₂O₂ has limited efficiency in complex matrices such as industrial wastewater, it can achieve satisfactory removal in simpler water matrices [18] such as municipal wastewater.

GAC filtration is a well-established adsorption technology, widely recognised for its robustness and operational simplicity. Its application for wastewater treatment has been consistently reported to achieve more than 80 % removal of micropollutants, both in laboratory-scale studies and in pilot-scale applications [19,20]. GAC is one of the most reliable options for advanced treatment, although its effectiveness may vary depending on the characteristics of the influent water and the properties of micropollutants present [21].

In recent years, hybrid treatment technologies have emerged as a promising strategy to enhance performance and facilitate wider implementation. The integration of AOPs, including the photo-Fenton process, with GAC has been investigated and demonstrates good performance. This approach has enabled compliance with regulatory removal targets, the elimination of transformation by-products, reduced overall process time, and an extended operational lifetime of GAC [22,23].

Most of these studies, however, have primarily focused on the removal efficiency of micropollutants. Although removal efficiency is a key parameter, it is not sufficient to determine the most suitable technology for implementation in WWTPs. To ensure a robust assessment of treatment alternatives, a more comprehensive perspective is required, one that integrates environmental impacts and economic aspects alongside removal performance. Life Cycle Assessment (LCA) offers a robust methodology for evaluating environmental impacts in a comprehensive and standardised manner. Following ISO 14040 and 14044 standards enables systematic quantification of potential environmental effects throughout the whole life cycle of a product, process, or service. Its application has proven particularly valuable in supporting environmental decision-making [24,25].

A few studies have applied LCA to AOPs for micropollutant removal, but these have been limited either to laboratory scale, generally not exceeding 50 L [24], or to theoretical assessments without experimental validation [26,27]. A previous review [28] has also highlighted this limitation, stressing the scarcity of full-scale and long-term evaluations under comparable conditions. In the case of GAC, studies have focused mainly on its production stage, rather than on its performance application in the wastewater treatment process [29,30]. This work addresses this gap by developing an LCA under realistic conditions in a large-scale pilot plant operated with commercial chemicals. These conditions allow a robust comparison between the stand-alone technologies and the combination. The combination of AOP and GAC has been previously reported to enhance performance due to synergistic effects. Thus, assessing their environmental and economic implications provides valuable insight when compared with stand-alone systems.

The present study contributes to closing this gap by conducting a comparative LCA of pilot-scale systems applying AOPs and GAC in a real scenario at Heiderscheidergrund WWTP (Luxembourg). The pilot plant in this study was operated continuously for more than five months, treating a minimum of 4 m³ day⁻¹ and removing up to 80 % micropollutants [19]. By generating reliable pilot-scale data, this work contributes directly to the objectives of the European Water Resilience Strategy, which emphasises the need for practical demonstration and scaling of innovative water technologies.

Beyond environmental performance, cost assessment is also critical

to ensure both the effectiveness and long-term sustainability of these technologies. Integrating LCA with cost analysis provides a comprehensive perspective, supporting decision-making on the applicability of these options.

The objectives of this study are therefore: (i) to evaluate environmental impacts by a LCA of the pilot plant, including both stand-alone and coupled AOP+GAC configurations; (ii) to compare the environmental impacts of the six scenarios, covering photo-Fenton, UV/H₂O₂, and the use of both fresh and regenerated GAC; (iii) to conduct a sensitivity analysis on the most critical parameters; and (iv) to analyse the costs associated with each scenario.

2. Materials and methods

2.1. Pilot plants description and treatment scenarios

A large-scale pilot plant was installed as quaternary treatment at Heiderscheidergrund WWTP (13,000 PE) (Luxembourg). It was operated in continuous mode over a six-month period between March and August 2023. The system consisted of two parallel lines: one comprising only GAC filtration and a second coupling an AOP-photo-Fenton or UV/H₂O₂- with GAC filtration. In both lines, fresh and regenerated GAC were investigated. Full details of the system design are available in N  nez-Tafalla et al. [19]. A schematic layout of the system is provided in the [supplementary information](#) (SI) (Figure SI 1).

Two GACs were studied in the stand-alone filtration system: fresh (CarboTech DGF 8x30GL) and regenerated (CarboTech Pool W1-3) GAC. Additionally, two AOP scenarios were selected: UV/H₂O₂ dosing 20 mg L⁻¹ of H₂O₂, and photo-Fenton dosing 3 mg L⁻¹ of iron and 40 mg L⁻¹ of H₂O₂. These scenarios were coupled with the same GAC sources as the stand-alone ones. The selected conditions are those that achieved the most robust outcomes in a previous work [19]. Given the promising results observed across the tested scenarios, a comprehensive evaluation of both environmental impacts and economic costs was essential to support technology selection. Thus the selected scenarios are: Fresh GAC stand-alone (F GAC), Regenerated GAC stand-alone (R GAC), photo-Fenton coupled with fresh GAC (PF + F GAC), photo-Fenton coupled with regenerated GAC (PF + R GAC), UV/H₂O₂ coupled with fresh GAC (UV/H₂O₂ + F GAC) and UV/H₂O₂ coupled with regenerated GAC (UV/H₂O₂ + R GAC).

The characteristics of the water matrix in the inlet and the outlet of the WWTP are summarised in Table SI 1.

2.2. Environmental analysis: life cycle assessment methodology

The environmental impact in this document is evaluated via the LCA standardised procedure outlined in the ISO 14040 and ISO 14044 standards. In accordance with it, the structure of this document follows the four main phases: (i) objective and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of the results.

2.2.1. Goal and scope definition

The goal of the LCA of this work is to evaluate the environmental impacts associated with the construction and operation of the two lines of the pilot plant described above, to compare the environmental impacts associated with each scenario.

The functional unit, used for the comparison of scenarios, was defined as the 80 % removal of 6 selected micropollutants in 1 m³ of effluent of the WWTP. This functional unit is based on the objective of the new EU Urban Wastewater Treatment Directive [2], where this target of removal is required. The six selected micropollutants comprise carbamazepine (CAS No 298-46-4), clarithromycin (CAS No 81103-11-9), diclofenac (CAS No 15307-86-5), metoprolol (CAS No 37350-58-6), benzotriazole (CAS No 95-14-7), and Tris (2-chloroisopropyl) phosphate (TCPP) (CAS No 13674-84-5), good

indicators for advanced oxidation efficiency and present in high concentrations.

Since the objective is to evaluate the environmental impact associated with each scenario, without considering the consequences of potential decisions or actions, an attributional modelling approach was selected [31,32].

The system boundaries of the scenario F GAC and R GAC are shown in Fig. 1a and the system boundaries for the PF + F GAC, PF + R GAC, UV/H₂O₂ + F GAC, and UV/H₂O₂ + R GAC are shown in Fig. 1b. The boundaries include the construction of the pilot plants and their operation, thus the scope is cradle-to-use. Due to the diverse origins of the materials and to ensure that the results were not influenced by the suppliers' proximity or distance, transportation was excluded from the system boundaries.

2.2.2. Life cycle inventory

The LCI was elaborated considering several data sources: provider documentation, data from recognised institutions, estimations based on material volumes and densities, relevant literature, and estimation based on information from other providers. The data sources were classified depending on their quality in Table SI 2 ([supplementary material](#)). The data source of the construction phase of the two pilot lines (Table SI 3 and SI 4) was obtained principally from supplier specifications as well as from volume and density estimation. However, for some small instruments, such as flowmeters, the material composition had to be selected from similar products from other suppliers due to the absence of exact specifications. The AOP pilot plant inventory includes all UV lamps required over the estimated 20-year operational lifetime of the system, which is assumed for both lines.

The operational phase (Table SI 5-7) covers all input and output items previously described in the system boundaries, with data classified as quality level A, as most of the parameters were directly measured on-site during pilot plant operation. An exception was the GAC production and regeneration inventory, which is secondary data from a previous study [33]. This study was selected because its process description aligns with that provided by CarboTech, the supplier, although specific process details remain confidential. A 15 % weight loss is assumed in each regeneration. Both production and regeneration are assumed to occur at CarboTech's facilities in Essen, Germany. The electric mix used was the Luxembourgish mix in 2023 [34], which reflects a combination of energy inputs from Luxembourg, Germany, Belgium, and France.

2.2.3. Life cycle impact assessment

The LCIA was conducted using the SimaPro 9 software. The Product Environmental Footprint LCIA method, and all of its environmental impact categories, was applied to ensure a standardised and comprehensive assessment of environmental impacts, ensuring alignment with the EU recommendation [35]. In this study, the global normalisation factors adopted in the Environmental Footprint method were applied to facilitate the selection of the most relevant impacts.

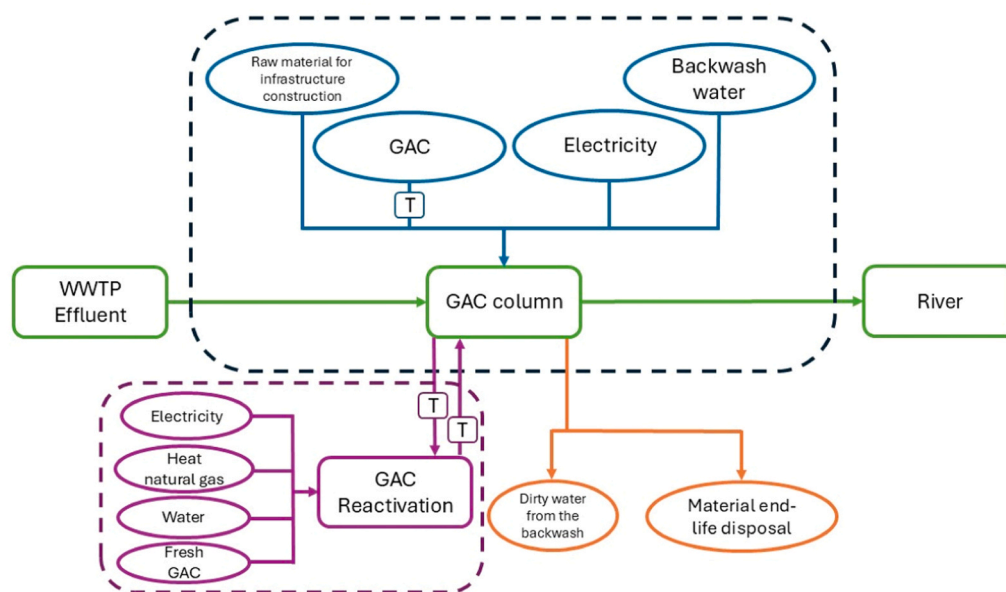
The impact categories considered in this study are Global Warming (GHG), Ozone depletion (ODP), Ionising radiation (IRP), Photochemical ozone formation (POCP), Respiratory inorganics (PMF), Non-cancer human health effects (HTP-NC), Cancer human health effects (HTP-C), Acidification terrestrial and freshwater (AP), Eutrophication freshwater (F-EP), Eutrophication marine (M-EP), Eutrophication terrestrial (T-EP), Ecotoxicity freshwater (FETP), Land use (LU), Water Resource Depletion (Water Scarcity) (W-RD), Resource use, energy carriers (E-RD) and Resource use, mineral and metals (M-RD).

Due to the possible influence of key assumptions on the different impacts, a sensitivity analysis was carried out in accordance with ISO 14040 and 14044 standards to evaluate the robustness of the results.

2.3. Economic assessment

The economic evaluation includes both capital expenditure (CAPEX)

a)



b)

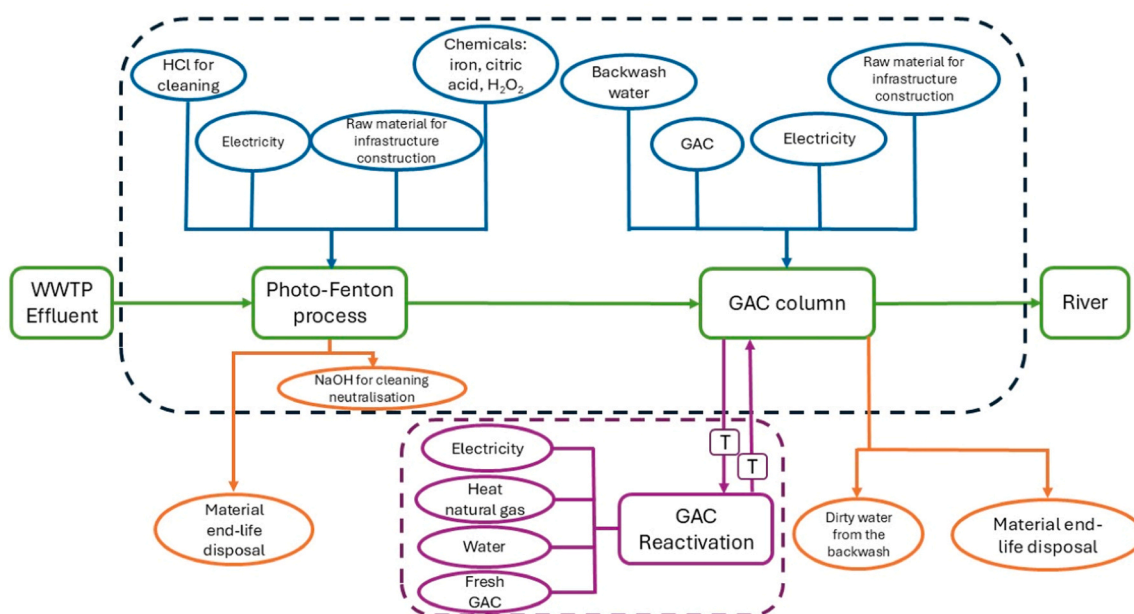


Fig. 1. System boundaries: (a) GAC filtration, (b) coupling of technologies. Dashed lines indicate the boundaries of the system under analysis. Colours represent: blue – materials and chemicals; green – water flow; orange – system outputs; purple – processes and resources related to GAC reactivation.

and operational expenditure (OPEX), expressed as cost per m^3 of treated water. CAPEX refers to the initial investment associated with the construction and installation of the pilot plant (Table SI 8). This cost was amortised using the Capital Recovery Factor (CRF) (Equation SI 1 and SI 2) method based on a 20-year lifetime and a 3 % discount rate.

OPEX includes all recurring expenses required to operate the system, such as energy, consumables, labour, and maintenance (Table SI 9). In addition to the operations considered, maintenance was assumed to be 3 % of the pilot plant construction cost over a 20-year period.

All costs are presented by cubic meter of treated water, calculated based on the treatment capacity of the pilot plant: 4 m^3 per day for GAC

columns and 20 m^3 per day for AOP, operating 365 days per year. Constant prices were assumed and inflation was ignored.

3. Results and discussion

3.1. Life cycle assessment results

The LCIA results are presented in this section. First, each scenario was evaluated independently to identify the main contributions to environmental impacts. This approach allows the easy identification of critical stages, processes or inputs where targeted improvements could

significantly reduce the overall footprint. Secondly, a comparative analysis of the scenarios was carried out, focusing exclusively on the most significant impacts, selected via normalisation of the results. All results discussed in the following sections refer to the functional unit (80 % micropollutants removal in 1 m³) defined for the study. A fixed removal efficiency ensured a comparable basis among technologies. Scenarios including the AOP + GAC combination required less frequent replacement, reducing material consumption and environmental impacts.

3.1.1. Evaluation of the treatment scenarios

Fig. 2 illustrates the contribution of each subsystem to the total environmental impact generated by each scenario. Detailed results are included in Tables SI 10–15. The subsystems (unitary processes) established are: electricity mix, H₂O₂, AOP pilot plant, iron chelated, GAC, GAC pilot plant, AOP cleaning and GAC backwash. Figs. 2a and 2b show

the results for scenarios involving fresh and regenerated GAC, respectively. In both options, energy emerges as a major contributor, despite considering exclusively the energy used for the pilot plant operation. Energy demand is mainly related to the pump, which feeds the columns and provides pressure to ensure a constant flow within the closed columns. The construction of the GAC system was identified as the second source of impact for several categories, including M-RD (96 %), W-RD (48 %), FETP (68 %), HTP-C (87 %), and HTP-NC (58 %). A detailed analysis of the construction stage (Fig. 3a) shows that all structural components contributed similarly across the impact categories. The main contributors were the columns and the pump, accounting up to 62 % and 55 %, respectively, although the percentage varied according to the impact categories. Within the columns, screws were mainly responsible for the impact. Screws and several pump components were made of stainless steel. Thus, substituting these elements with materials of lower environmental burden could substantially reduce the overall

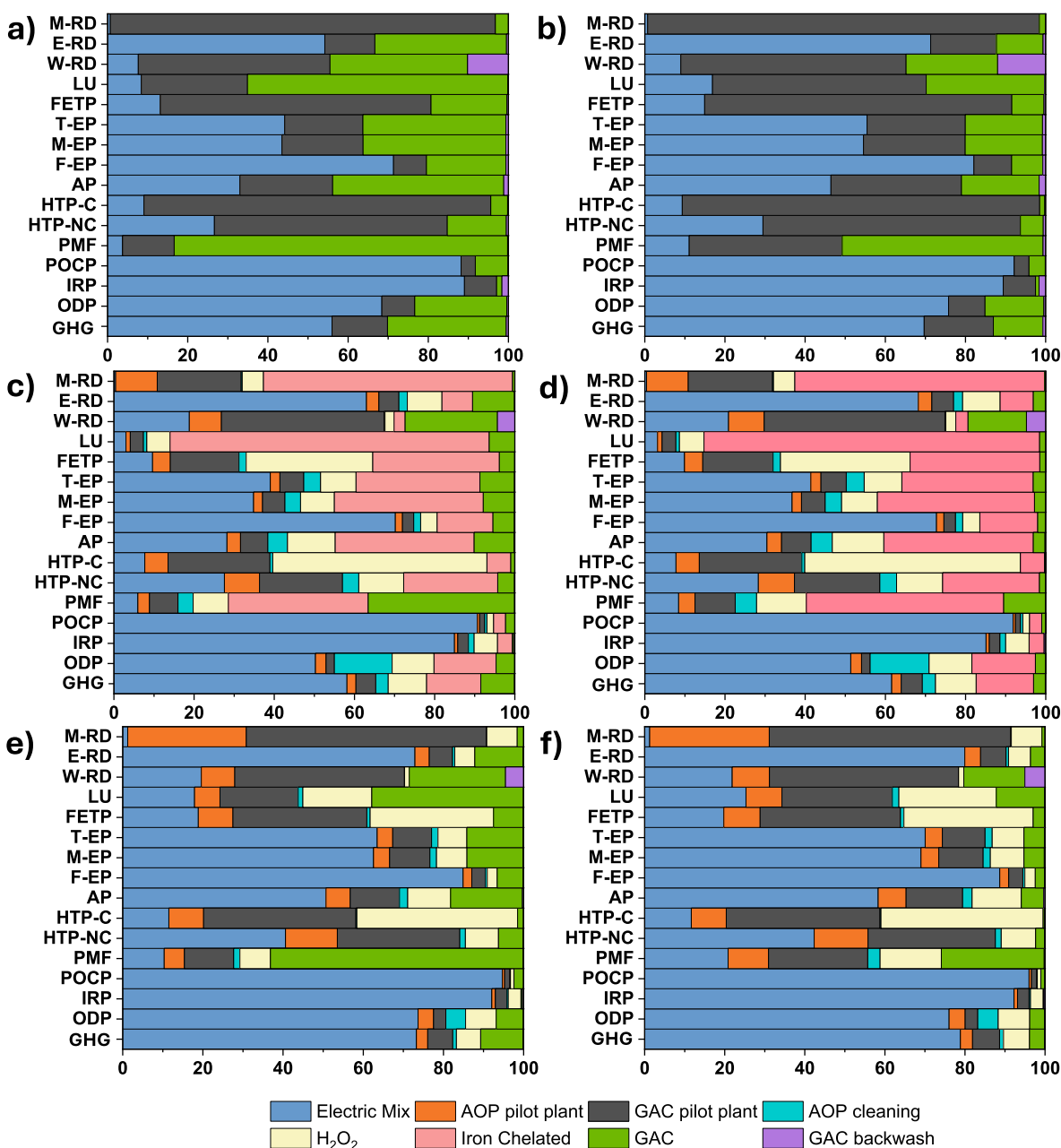


Fig. 2. Contribution of each element to the total environmental impact generated by each system studied: a) F GAC, b) R GAC, c) PF+F GAC, d) PF+R GAC, e) UV/H₂O₂+F GAC, f) UV/H₂O₂+R GAC.

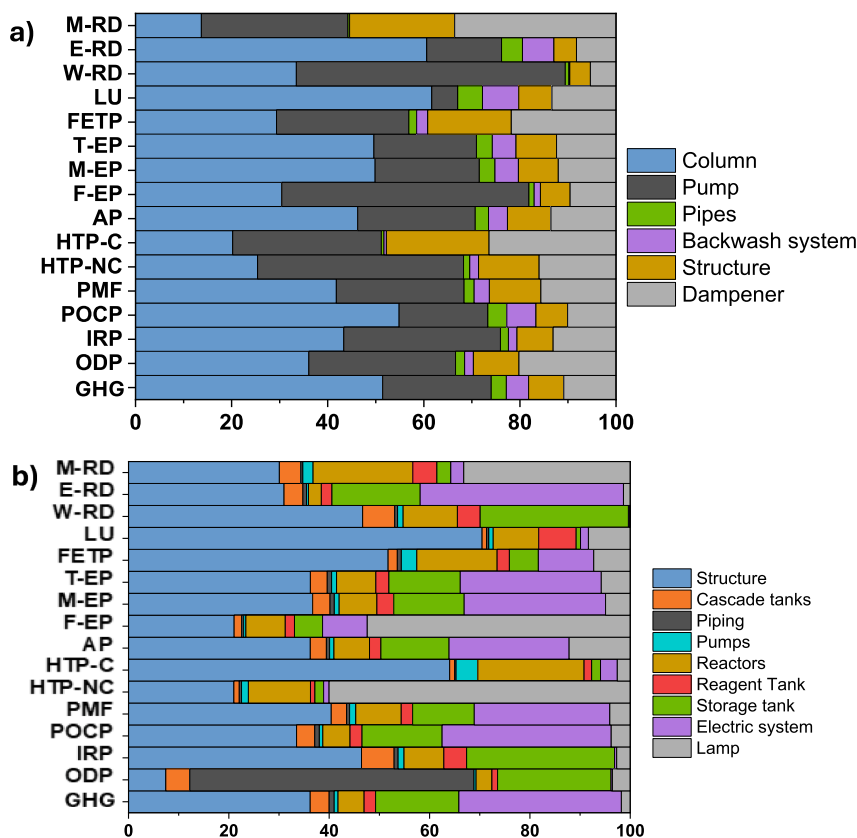


Fig. 3. Contribution of each subsystem to the total environmental impact of the a) GAC pilot plant construction, b) AOP pilot plant construction.

impact. Previous studies have proposed the use of recycled stainless steel as an effective strategy to reduce its environmental impact [36].

The third main source of impact is the fresh GAC production process, which contributed notably to LU and PMF. As shown in Fig. 2b, using regenerated GAC reduced the relative environmental impact in all categories, from 65 % to 53 % for LU and from 83 % to 50 % for PMF (fresh and regenerated GAC, respectively). This reduction was achieved even after the addition of 15 % fresh GAC required to compensate for losses during regeneration.

In scenarios where AOP were coupled with GAC filtration (Fig. 2c-f), energy also emerged as one of the most significant causes of the impacts. The affected categories were E-RD, T-EP, M-EP, F-EP, AP, POCP, IRP, ODP, and GHG, with contributions reaching 40 % in all cases and even 90 % in some of them, such as POCP. Due to the high-intense energy requirements of AOPs, but also ozonation, it is commonly described as the main source of impact [26]. For the AOP system, the cascade configuration required four pumps to supply water to the different loops, consuming more energy than the lamp irradiation. This design issue, which was previously noted by Notarnicola et al. [37], underscores the importance of optimising the technology configurations to minimise energy demand.

Beyond energy, chemical reagents also played a relevant role in several impact categories. Previous authors have reported this fact, which in solar photo-Fenton is the principal source of environmental impact [38]. Chelated iron (iron: citric acid (1:2)) showed considerable contributions to LU and PMF (up to 35 and 10 %, respectively), principally associated with the environmental footprint of citric acid production. This compound is typically synthesised from biomass-based feedstocks such as wood sugars or corn, whose production is linked with these impacts [39,40]. In addition, iron also had a significant influence on these impacts, as reported by Haque and Norgate [41]. On the other hand, H_2O_2 contributed notably to HTP-C (57 % for PF and 40 % for UV/ H_2O_2 process), which was also caused by the energy demand

associated with its production [42]. These findings highlight the importance of minimising chemical doses not only to save on operational costs, but also to reduce the environmental impacts of the AOP process itself.

Fig. 3b shows the impacts related to the AOP system construction. In this case, the supporting structure of the system was found to be the most significant factor across all categories (between 19 % and 70 %), except ODP (7 %). The second largest contributors varied by impact category and included the storage tank, the reactor, and the UV lamp.

As shown in Fig. 2, the construction of the AOP system had a lower overall environmental impact than the GAC pilot plant, despite the higher complexity of the technology. This difference is probably related to the difference in design capacity (treated volumes, $4 \text{ m}^3 \text{ day}^{-1}$ for GAC filtration and $19 \text{ m}^3 \text{ day}^{-1}$ for AOP). When impacts are normalised by the functional unit, higher treatment capacity will show a lower construction impact due to dilution across a larger functional unit.

For both systems, operational procedures, such as backwashing or lamp cleaning, have a minor influence on the system's impact (less than 10 % in any case).

3.1.2. Comparison of the different scenarios

The six previously described treatment scenarios were compared to identify the most environmentally sustainable configuration. Figure SI 2 presents the normalised impacts under the Environmental Footprint method and its normalisation factors [43]. The most influential categories across all cases were HTP-C, GHG, POCP, E-RD, and W-RD. A comparison of the five normalised impact categories across scenarios is shown in Fig. 4.

On these impacts, the R GAC showed lower environmental impacts than F GAC, even with its shorter lifetime (15,400 bed volume and 16,800 bed volume for R GAC and F GAC, respectively). Across all analysed categories, R GAC consistently exhibits the lowest impact. This outcome is consistent with previous findings highlighting the benefits of

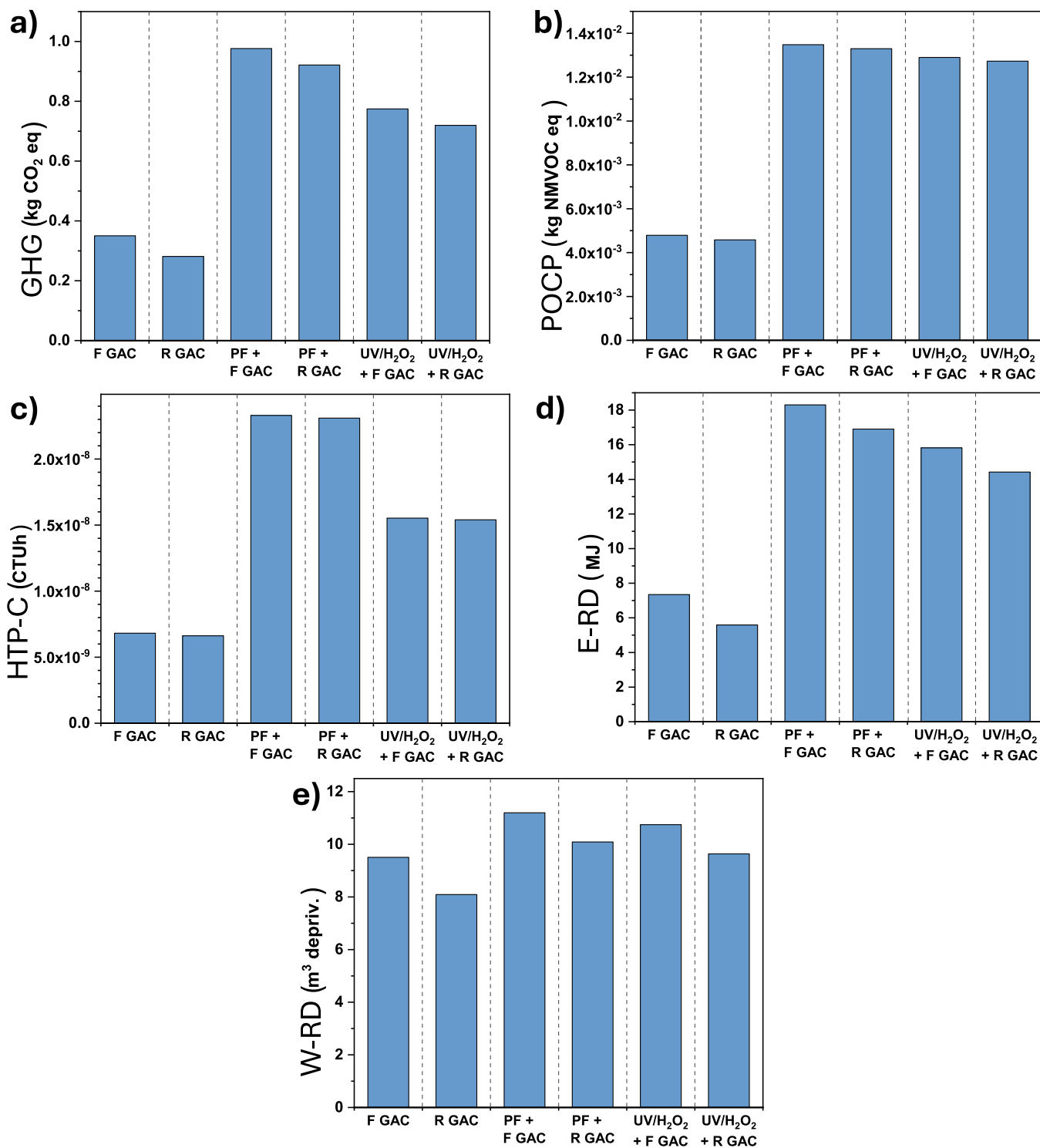


Fig. 4. Effect of the different scenarios on the selected impacts: a) GHG, b) POCP, c) HTP-C, d) E-RD, d) W-RD.

using regenerated GAC to reduce environmental impacts [44,45]. The UV/H₂O₂ system showed a lower overall impact than the photo-Fenton process. Multiple factors, including a higher frequency of cleaning and the use and production of iron sulphate and citric acid, cause this difference. Additionally, the photo-Fenton configuration requires two separate chemical dosing systems (for chelated iron and H₂O₂), whereas UV/H₂O₂ needs only one.

Looking at the impacts individually, the highest variation between scenarios was observed in the HTP-C category, where the photo-Fenton is 40 % higher than UV/H₂O₂ process. In the other four impact

categories, differences are below 10 %. For AOP, HTP-C was primarily associated with chemical use, and as the photo-Fenton requires both H₂O₂ and chelated iron, the effect on HTP-C substantially increased.

The smallest difference between scenarios was observed for W-RD, where the effect of the GAC stand-alone was nearly equivalent to that of the coupled AOP-GAC process. The W-RD values were 9.5, 8.1, 10.9, 9.8, 10.7, and 9.6 m³ deprivation for F GAC, R GAC, PF+F GAC, PF+R GAC, UV/H₂O₂+F GAC, and UV/H₂O₂+R GAC, respectively. This similarity can be a consequence of the main role of the GAC system in this impact category, associated with pilot plant construction and GAC

production. In the coupled scenarios, longer GAC lifetimes, up to 26 %, compensated for the additional impacts introduced by the AOP system. The difference between F GAC and R GAC in this category remained marginal. These results are consistent with previous studies indicating that the water depletion impact of GAC is primarily linked to its activation process, which requires significant quantities of steam during thermal treatment [30,46].

GHG, POCP, and E-RD show similar differences across the scenarios, with energy being the main contributor in all three categories.

3.1.3. Sensitivity analysis

A sensitivity analysis was conducted to assess the impact of certain assumptions on the existing LCA scenarios. Two main factors were examined: the electricity mix during operation and the GAC production inventory. These parameters were chosen because they significantly affect the overall impacts and may introduce variability in the results.

Regarding electricity supply, two opposite approaches were defined: one assuming 100 % renewable energy and another assuming 100 % fossil-based energy. These scenarios were created by proportionally modifying the Luxembourg electricity mix used in the main analysis. The renewable energy approach aligns with the objectives of the revised EU Urban Wastewater Treatment Directive [2], which promotes a full transition to renewable energy sources in WWTPs. The use of 100 % fossil-based approach was selected as the worst scenario for the production of electricity.

In terms of GAC production, the approach adopted LCI data from another published source [46], which differ in the energy and production requirements used during the thermal activation process.

Table 1 presents the percentage variation observed in the most relevant impact categories (HTP-C, GHG, POCP, E-RD, and W-RD) with respect to the initial evaluation. Positive values indicate an increase in environmental impact, while negative values denote a reduction.

The results indicate that a change in the electricity mix leads to significant changes in most of the impact categories. GHG was the most affected, which is consistent with previous findings [24,47] that emphasise the importance of energy sources as a key parameter for climate change. Consequently, replacing the Luxembourgish electricity mix with fossil-based energy increases GHG between 123 % and 173 % and E-RD between 48 % and 71 %. In contrast, the use of renewable

Table 1

Variation of the key impacts for each scenario, when different energy sources, carbon origins and production are considered.

	F GAC	R GAC	PF + F GAC	PF + R GAC	UV/H ₂ O ₂ + F GAC	UV/H ₂ O ₂ + R GAC
Renewable electricity						
GHG	-51 %	-64 %	-53 %	-56 %	-67 %	-72 %
POCP	+ 62 %	+ 65 %	+ 64 %	+ 65 %	+ 67 %	+ 68 %
HTP-C	-5 %	-5 %	-4 %	-4 %	-7 %	-6 %
E-RD						
E-RD	-53 %	-70 %	-61 %	-66 %	-71 %	-78 %
W-RD						
W-RD	-8 %	-9 %	-19 %	-21 %	-20 %	-22 %
Fossil-fuel						
GHG	+ 123 %	+ 153 %	+ 128 %	+ 135 %	+ 161 %	+ 173 %
POCP	-77 %	-81 %	-79 %	-80 %	-83 %	-84 %
HTP-C	+ 12 %	+ 13 %	+ 10 %	+ 10 %	+ 16 %	+ 16 %
E-RD						
E-RD	+ 48 %	+ 63 %	+ 56 %	+ 61 %	+ 65 %	+ 71 %
W-RD						
W-RD	+ 18 %	+ 21 %	+ 43 %	+ 48 %	+ 45 %	+ 50 %
Other inventory GAC [46]						
GHG	+ 63 %	+ 7 %	+ 18 %	+ 2 %	+ 22 %	+ 2 %
POCP	+ 52 %	+ 7 %	+ 15 %	+ 2 %	+ 15 %	+ 2 %
HTP-C	+ 41 %	+ 4 %	+ 13 %	+ 1 %	+ 15 %	+ 1 %
E-RD						
E-RD	+ 14 %	+ 2 %	+ 3 %	+ 0 %	+ 5 %	+ 0 %
W-RD						
W-RD	+ 451 %	+ 75 %	+ 303 %	+ 47 %	+ 316 %	+ 49 %

sources substantially lowers GHG and E-RD impact, with decreases ranging between 51 % and 72 % and 53 and 78 %, respectively. The effect on HTP-C impact was almost negligible (reduction between 4 % and 7 %) since the impact category is primarily driven by the use of chemical reagents rather than energy, as previously discussed. POCP is the only impact where renewable energy has a slightly negative influence, while fossil fuel-based energy results in a positive influence, caused by the contributions from photovoltaic and geothermal technologies included in the renewable mix [48].

Regarding the production of GAC, using an alternative LCI source results in relevant effects. The variations were particularly evident when using fresh GAC, where the impacts increased in all categories. W-RD showed the most significant increase, where the increment has a high variability depending on the scenario, from 47 % in some of the PF + R GAC to 473 % in the F GAC scenario. As previously identified, the main contributors to W-RD in GAC systems are the construction of the pilot-scale filtration unit and the production of GAC. The higher steam requirements during thermal activation reported by Goyal et al. [46] amplify the impact on the production. These findings highlight the need for optimisation strategies in GAC manufacturing processes, specifically, the reduction of the water steam required for activation is critical.

3.2. Cost assessment

A preliminary calculation of CAPEX and OPEX was performed to provide an economic assessment of the alternative technologies of the pilot-scale system. These calculations are intended as a preliminary evaluation at pilot scale, aiming to identify the main cost drivers that must be considered in any future scale-up. CAPEX was derived from the actual construction of the pilot systems, whereas OPEX was calculated based on unit prices (Table SI 8 and SI 9).

Both photo-Fenton and UV/H₂O₂ were included within the AOP system category since both processes were operated with the same pilot plant. The total cost of the AOP system exceeded that of GAC, reflecting the higher complexity of the oxidation process (Table SI 8). However, when normalised to the volume of water treated, AOP represented lower costs (0.52 €·m⁻³) than GAC (2.14 €·m⁻³), as the treatment capacity of the GAC system was smaller, as previously described. Previous research reported that investment costs do not scale proportionally with capacity, leading to lower unit costs at higher volumes [49,50]. This remark suggests that the unit costs obtained in this study, which are higher than those reported in the literature, would likely decrease if scaled up, approaching the ranges of 0.035–0.05 €/m³ reported by Rizzo et al.

Table 2

CAPEX and OPEX of the different scenarios (cost per m³).

Cost (€ m ⁻³)	F GAC	R GAC	PF + F GAC	PF + R GAC	UV/ H ₂ O ₂ + F GAC	UV/ H ₂ O ₂ + R GAC
CAPEX	2.15	2.15	2.67	2.67	2.67	2.67
OPEX						
Energy	0.18	0.18	0.62	0.62	0.60	0.60
Materials and reagents						
GAC	0.06	0.05	0.05	0.04	0.05	0.04
Iron	–	–	0.008	0.008	–	–
Citric acid	–	–	0.022	0.022	–	–
H ₂ O ₂	–	–	0.017	0.017	0.009	0.009
HCl	–	–	0.028	0.028	0.0007	0.0007
NaOH	–	–	0.0032	0.0032	0.0007	0.0007
Total	0.06	0.05	0.13	0.12	0.06	0.05
Lamps	–	–	0.10	0.10	0.10	0.10
Total consumables	0.24	0.23	0.98	0.96	0.82	0.80
Maintenance	0.09	0.09	0.11	0.11	0.11	0.11
Operation	1.17	1.18	1.37	1.38	1.08	1.08
Total labour	1.26	1.27	1.48	1.49	1.19	1.19
Total OPEX	1.50	1.50	2.46	2.45	2.01	1.99

[51].

With respect to OPEX (Table 2), the results showed that consumable costs were lower than labour costs across all scenarios. For both GAC, the main consumable costs were associated with GAC purchase and energy, with the latter representing the largest cost (75 %). Differences between F GAC and R GAC were limited. Although R GAC required more frequent replacement due to its shorter lifetime, its cost remained slightly lower, at 0.05 € m⁻³ for regenerated GAC compared to 0.06 € m⁻³ for fresh GAC. Operator labour, including manual backwashing and replacement of spent GAC, accounted for a relatively high share of the operating costs (1.26 € m⁻³). Inanes et al. [7] already indicated that consumables, particularly GAC purchase or regeneration, are usually the dominant contributors to operating costs, whereas in this study, labour was shown as the most important input. Thus, automation is shown as a key factor for reducing costs at larger scales.

For the coupled scenarios (AOP+GAC), higher costs are attributed to energy consumption due to the use of lamps as irradiation source. In these hybrid systems, energy consumption was approximately five times more costly than reagents, including the cleaning products for equipment maintenance. Energy costs were 0.62 € m⁻³ for PF+GAC and 0.60 € m⁻³ for UV/H₂O₂+GAC, whereas reagent costs ranged between 0.12–0.13 € m⁻³ for PF+GAC and 0.05 € m⁻³ for UV/H₂O₂. The costs estimated for PF+GAC are consistent with the upper range reported by Soriano-Molina et al. [52] for solar photo-Fenton (0.11–0.47 € m⁻³), which included reagents and pumping electricity, not including equipment cleaning, nor energy consumption related to irradiation.

For UV/H₂O₂, the cost of the coupled system resulted in 0.80–0.82 € m⁻³, which is higher than the range of 0.12–0.18 € m⁻³ reported by Rizzo et al. [51]. In that study, the values refer to a full-scale system and considered only reagents and irradiation energy, but excluding the costs of pumping as well as lamp replacement after 14,000 hours of operation.

Finally, labour also represented a large fraction of OPEX in the coupled scenarios, as operator intervention was required for lamp cleaning and backwashing in AOP and GAC, respectively. The literature suggests that maintenance accounts for 3–4 % of operational costs [53], whereas in this study, labour represented nearly 60 % of OPEX. Although these values may vary depending on regional salary structures, the findings highlight that for both systems, automation of maintenance and cleaning operations will be essential to reduce costs during scale-up.

The comparison of the different treatment scenarios highlights that the coupling of PF+GAC results in a substantially higher cost than stand-alone GAC filtration, by approximately 1 € m⁻³. In contrast, the cost difference between UV/H₂O₂+GAC and stand-alone GAC filtration is slightly smaller, 0.5 € m⁻³; thus, GAC was the cheapest technology. However, other factors beyond cost, such as disinfection or reuse of water, should be considered when choosing the most suitable technology. No significant cost differences were observed between F GAC and R GAC, emphasising the need for a holistic evaluation.

4. Conclusions

This study evaluated the environmental impacts and costs of six treatment scenarios to remove 80 % of some of the micropollutants targeted by the EU Urban Wastewater Treatment Directive [2]. Environmental impact was assessed using LCA, which identified GHG, POCP, HTP-C, E-RD, and W-RD as the most affected impact categories. Energy consumption was the main contributor across all scenarios, reinforcing the importance of the transition to renewable energy sources promoted by the energy neutrality objective of the previously cited EU Directive. In fact, the sensitivity analysis further demonstrated that GHG impacts could be reduced by up to 72 % if a transition to renewable energy is made. In addition, it was revealed that the use of regenerated GAC is advantageous for all impact categories, even though it requires more frequent replacement compared to fresh GAC. These findings underline that the environmental performance of quaternary treatment technologies is highly dependent on contextual factors, including national energy

policies and the specific processes used for GAC production.

Economical assessment showed that GAC filtration was the cheapest option, independently of whether fresh or regenerated GAC was used. When jointly considering both environmental and economic dimensions, R GAC clearly emerges as the scenario with the best overall sustainability performance among those evaluated. However, certain limitations must be considered, such as the lack of disinfection capability and selective adsorption of micropollutants. To address these limitations, the coupled UV/H₂O₂+GAC process was shown as the most suitable alternative among the scenarios studied, offering a balance between environmental performance and treatment efficacy. Overall, despite being based on pilot-scale data, the findings demonstrate consistent and robust trends that are expected to hold under full-scale conditions. Thus, GAC should be prioritised as the preferred treatment option, while the coupled UV/H₂O₂+R GAC configuration offers a promising secondary choice when higher treatment capability is required.

CRedit authorship contribution statement

P. Núñez-Tafalla: Conceptualisation, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **I. Salmeron:** Investigation, Validation, Writing – review and editing. **J. Perez Rodriguez:** Methodology, Resources, Supervision, Writing – review and editing. **J. Rodriguez-Chueca:** Validation, Writing – review and editing. **S. Venditti:** Writing – review and editing. **J. Hansen:** Funding acquisition, Project administration, Writing – review and editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jorge Rodriguez-Chueca reports financial support was provided by European Commission. If there are other authors, they declare that they have not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2025.120644.

Data availability

Data will be made available on request.

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