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Life Cycle Assessment of a Cu/Fe-Pillared Clay Catalyzed Photo-Fenton Process for Paracetamol Removal

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Abstract

Due to its efficiency, advanced oxidation processes (AOP), such as photo-Fenton, have become an alternative for removing emerging contaminants like paracetamol. The objective of this work was to perform a life cycle assessment (LCA) according to ISO 14040/44 for a heterogeneous photo-Fenton process catalyzed by Cu/Fe-pillared clays (PILC) for the removal of paracetamol from water. The study covered catalyst synthesis and four treatment scenarios, with inventories built from experimental data and ecoinvent datasets; treatment time was 120 min per functional unit. Environmental impacts for catalyst synthesis were quantified with ReCiPe 2016 (midpoint), while toxicity-related impacts of the degradation stage were assessed with USEtox™ (human carcinogenic toxicity, human non-carcinogenic toxicity, and freshwater ecotoxicity). Catalyst synthesis dominated most midpoint categories, the global warming potential for 1 g of Cu/Fe-PILC was 10.98 kg CO_2 eq. Toxicity results for S4 (photo-Fenton Cu/Fe PILC) showed very low values: 9.73×10^{-12} CTUh for human carcinogenic and 1.29×10^{-13} CTUh for human non-carcinogenic. Freshwater ecotoxicity ranged from 5.70×10^{-4} PAF·m^3·day at pH 2.7 (≥60 min) to 1.67×10^{-4} PAF·m^3·day at pH 5.8 (120 min). Overall, optimizing pH and reaction time, are key levers to improve the environmental profile of AOP employing Cu/Fe-PILC catalysts.

Keywords: life cycle assessment; photo-Fenton; Cu/Fe-pillared clays; paracetamol; ReCiPe 2016; USEtox; freshwater ecotoxicity

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1. Introduction

Pharmaceutical contaminants, such as paracetamol (acetaminophen), have emerged as pollutants of growing concern due to their frequent detection across all environmental compartments including air, water, and soil and particularly in surface waters and wastewater systems worldwide [1–3]. Responsible management and disposal of pharmaceutical wastewater are essential to minimize chemical pollution, as the uncontrolled release of hazardous substances can lead to significant environmental degradation [4]. Acetaminophen, (as shown in Figure 1), is a widely used analgesic and antipyretic commonly prescribed for the symptomatic relief of mild to moderate pain [5]. Its therapeutic applications include the

treatment of sore throat, menstrual pain, post-vaccination discomfort, and pain associated with various medical procedures [6]. However, paracetamol enters aquatic environments primarily through human excretion, improper disposal, and discharges from pharmaceutical industries, hospitals, and municipal sources [7,8]. Although typically found at trace concentrations, these substances can pose ecotoxicological risks to aquatic organisms, even at low levels of exposure [9].

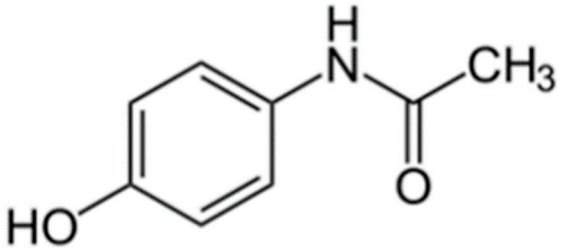


Figure 1. Chemical structure of paracetamol (acetaminophen).

Micropollutants such as pharmaceuticals are considered non-regulated contaminants that exhibit unique physicochemical characteristics and environmental behavior. These compounds are commonly discharged into sewer systems and transported with municipal wastewater to wastewater treatment plants (WWTPs) [10]. Due to the limited efficiency of conventional wastewater treatments in removing pharmaceutical residues, selecting an appropriate technology requires consideration of multiple factors, including treatment efficiency, cost, environmental safety, and process flexibility [11].

Currently, various methods have been applied for paracetamol degradation, including physical processes such as forward osmosis (FO), which utilizes a wide range of specialized membranes [12,13]. This technology is considered a promising paracetamol removal technology, as it presents an environmentally friendly, energy-efficient, and economically viable alternative. Biological methods have also been used to degrade paracetamol, mainly through microbial degradation processes using bacteria or enzymes [14]. Advanced oxidation processes have been widely used for the degradation of paracetamol and its intermediates, including photolysis [15], Fenton process [16], electro-Fenton (electricity) [17], photo-Fenton (UV light) [18], sono-Fenton (ultrasound) [19,20], and heterogeneous photocatalysis [21–23].

Table 1 summarizes the results obtained regarding paracetamol removal with different advanced oxidation processes. As observed, a high paracetamol removal is generally achieved. The removal rate is dependent on catalyst, pH, reaction volume, radiation wavelength and paracetamol initial concentration. It is important to note that while AOPs demonstrate high degradation efficiencies, they are also associated with high resources demands. These include significant energy consumption especially for light-based processes as well as the use of chemical reagents. Consequently, the environmental sustainability of AOPs should not be evaluated solely based on their removal efficiency, but also through a broader environmental perspective that considers their entire life cycle [24]. In this context, LCA has become an essential tool for evaluating and comparing treatment technologies from a holistic perspective [25]. LCA provides quantitative insight into resource use, emissions, and environmental burdens across the entire life cycle from catalyst synthesis and energy consumption to operational performance and waste generation.

Table 1. Summary of recent studies on paracetamol degradation: operational conditions, catalysts, and removal efficiencies.

Process	Wavelength, Photocatalyst and Its Concentration	Paracetamol Initial Concentration (g/L)	Reaction Conditions	Paracetamol, TOC Removal (%) and Treatment Time	Reference
Photo-Fenton	UV (254 nm) Cu/Fe-PILC 50 mg/L	0.1	pH = 3.0 T = 25 °C H_2O_2 = 483 mg/L pH = 5.8	100 (20 min) 85 (180 min) 100 (30 min) 81 (180 min)	[26]
	Visible light (100 W) CuO=C 1 g/L	1.21×10^{-3}	pH = 5.1 V = 0.1 L T = 23 ± 2 °C $H_2O_2 = 5 \times 10^{-3}$ mol/L	95 68 (480 min)	[27]
	UV (390 nm) Fe-SBA-15 0.33 g/L	0.02	V = 0.45 L $H_2O_2 = 1 \times 10^{-3}$ mol/L	86.1 (30 min)	[28]
	UV (365 nm) Fe/TiO_2_SCS 2 g/L	0.01	pH = 3 T = 25 °C $H_2O_2 = 2.78 \times 10^{-3}$ mol/L	100 (60 min)	[29]
Fenton	Fe@C_3N_4-montmorillonite 25 mg	0.04	pH = 6 V = 0.1 L Flow rate = 30 mL/min	>95 (2000 min)	[30]
Photocatalysis	Visible light (400 nm) CuBi/Ti_3C_2, 1 g/L	0.01	pH = 5.4 V = 0.05 L	99.7 99.9 (150 min)	[31]
	Visible light (318 mW/cm^2) NiO-TiO_2, 0.5 g/L	0.01	pH = 7	98.8 (240 min)	[32]
	UV Zr–WO_3@ charcoal 1 g/L	0.02	pH = 6 T = 25 °C	73 (120 min)	[23]
Catalytic wet peroxide oxidation	Fe/MCM-41 1 g/L	0.005	pH = 3 V = 1L T = 55 °C H_2O_2 (Stochiometric amount)	>90 (240 min)	[33]
	CNT@NiFeAl-C 2.5 g/L	0.1	pH = 3.5 V = 0.1 L T = 80 °C H_2O_2 = 474 mg/L	100 (60 min) 71% (360 min)	[34]

Besides paracetamol, Fenton and photo-Fenton processes have been widely studied due to their effectiveness in removing a wide range of contaminants [35–37]. The conventional homogeneous Fenton reaction involves the reaction of hydrogen peroxide (H_2O_2) with ferrous ions (Fe^{2+}) in aqueous solution, leading to the production of hydroxyl radicals (•OH) [38,39]. This process is commonly carried out at a pH of 3, since at pH > 3, iron hydroxides are formed, causing the iron to precipitate, forming sludge [35]. This is one of the main reasons for heterogeneous iron catalysts being widely used in Fenton processes. In addition to avoiding sludge generation, the heterogeneous catalysts reduce the chemicals required to maintain an acidic environment and prevent the precipitation of iron ions, thus eliminating the need for additional methods for sludge separation and final disposal [36]. Another significant advantage of using heterogeneous catalysts in the Fenton process is their easy recovery and reuse in subsequent reactions [36].

The photo-Fenton process, a light-assisted variant of the Fenton reaction, enhances radical generation through irradiation typically using UV or solar light resulting in improved degradation rates of persistent compounds [40]. Recent research has increasingly focused on this technology due to its potential for environmental and energy efficiency when coupled with solar energy [41,42]. Nonetheless, the application of photo-Fenton processes at full scale remains limited, as most existing studies have been conducted at the laboratory scale, often under controlled and idealized conditions [43].

In Fenton and photo-Fenton processes, the use of heterogeneous catalysts has been explored to reduce environmental trade-offs. In particular, metal-pillared clays (M-pillared clays), where M corresponds to transition metals such as Cu and Fe, have demonstrated promising catalytic performance in photo-Fenton reactions [44]. These materials offer improved surface area, thermal stability, and reusability, making them attractive candidates for scaling up advanced treatment technologies. However, despite their potential, little is known about their environmental sustainability when assessed from a life cycle perspective [45]. To date, most studies have focused on organic compounds removal efficiency, while overlooking the broader environmental implications associated with catalyst production and operational demands.

Therefore, this study aims to bridge this gap by conducting a LCA of a photo-Fenton process catalyzed by Cu/Fe-pillared clays for the removal of paracetamol from aqueous systems. The removal of paracetamol by this means has been previously reported by our group [26] and the inventory in this work is based on those experimental results. By integrating LCA with experimental data on catalyst performance, this work seeks to provide a more comprehensive understanding of the environmental trade-offs involved in deploying advanced heterogeneous AOPs for pharmaceutical wastewater remediation. For this purpose, the midpoint environmental impacts were established of treating wastewater containing a known concentration of paracetamol, using a photo-Fenton process catalyzed by Cu/Fe-pillared clays (PILCs), through a LCA methodology with methods: Recipe (midpoint) for catalysts synthesis and USEtox™ for Paracetamol degradation. To establish the environmental relevance of the photo-Fenton treatment, another three plausible scenarios were assessed: without treatment, photolysis, and photolysis plus hydrogen peroxide. To demonstrate the importance of operational variables like pH on the contribution to environmental impacts, a sensitivity analysis around this variable was also conducted.

2. Materials and Methods

A LCA was performed following the four standardized phases outlined in ISO 14040 and 14044 [46]: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation.

2.1. Goal and Scope of Study

The goal of the study was to assess a photo-Fenton process catalyzed by Cu/Fe-pillared clays for the removal of paracetamol. The environmental impacts were assessed across four scenarios: S1 (without treatment), S2 (Photolysis), S3 (UV-H_2O_2), and S4 (catalyst synthesis and photo-Fenton process catalyzed by Cu/Fe PILC). The functional unit was 1 L of aqueous solution containing 0.10 g of paracetamol. The analysis follows a cradle-to-gate approach.

The system boundary, as shown in Figure 2, includes all stages from the production and transport of chemicals and materials (e.g., catalysts, reagents, energy inputs) to the point at which the treated effluent is ready for discharge or further treatment. End of life processes, such as final effluent discharge into receiving water bodies, were not included in this assessment.

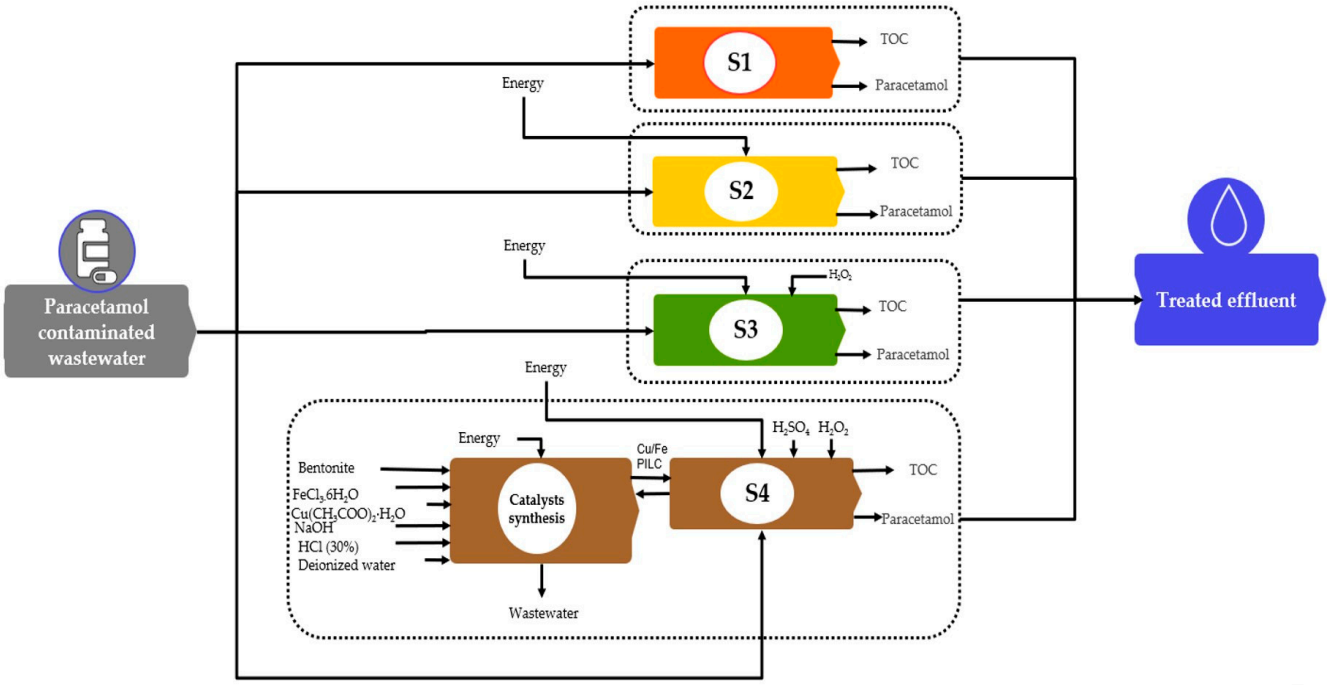


Figure 2. System boundary of treatment scenarios for paracetamol degradation: S1 (without treatment), S2 (Photolysis), S3 (UV-H_2O_2) and S4 (catalyst synthesis and photo-Fenton process catalyzed by Cu/Fe PILC).

2.1.1. Catalysts Synthesis

According to the synthesis procedure reported by Hurtado et al. [26] and Valverde et al. [47], iron pillared clays (Fe-PILC) were prepared as follows: a 0.3 L aqueous solution of $FeCl_3 \cdot 6H_2O$ was gradually mixed with 0.6 L of 0.2 M NaOH under continuous stirring at room temperature. The resulting mixture was stirred for 4 additional hours at room temperature, with the pH adjusted to 1.7 using 5 M HCl, to inhibit the precipitation of Fe species. The pillaring solution was then added dropwise to a 0.1 wt% bentonite suspension, followed by 12 h of continuous stirring. The solid product was recovered by centrifugation and washed with deionized water until the conductivity dropped below 5 µS/cm. This step was carried out to eliminate any remaining chloride ions that could limit the diffusion of polyoxocations into the interlayer space [48]. Finally, the material was dried overnight at 74 °C and calcined at 400 °C for 2 h.

2.1.2. Paracetamol Degradation

The photo-Fenton degradation experiments of paracetamol were conducted following the methodology reported by Hurtado et al. [26]. A cylindrical Pyrex glass reactor (20 cm in length, 2.5 cm in diameter) was used, containing 100 mL of an aqueous paracetamol solution at an acetaminophen initial concentration of 100 ppm. The system temperature was maintained at 298 K using a thermostatic bath. Illumination was provided by an 8 W high-pressure mercury lamp (UVP-Pen Ray Model 3SC-9, Analytik Jena, Tewksbury, CA, USA), emitting light at 254 nm, positioned along the central axis of the reactor. Stirring was maintained at 800 rpm throughout the experiment. In a typical run, the paracetamol solution was first introduced into the reactor, followed by the dispersion of 0.050 g of the Cu/Fe-PILC catalyst. When acidic conditions were required, the pH was adjusted using 0.1 M H_2SO_4. Illumination and the addition of a stoichiometric amount of hydrogen peroxide (H_2O_2) (145 µL) were initiated simultaneously. During the reaction, samples were collected at regular intervals to monitor the degradation of paracetamol and the formation of by-products, as well as to evaluate the extent of mineralization.

2.2. Life Cycle Inventory Assessment (LCI)

To generate the experimental primary quality for different scenarios for S1 (without treatment, see Table 2), S2 (photolysis (UV), see Table 3), S3 (UV + H_2O_2, see Table 4), and S4 (Catalyst synthesis and photo-Fenton process catalyzed by Cu/Fe PILC, see Table 5). The inputs and outputs of reagents, catalysts synthesis (Cu-Fe-PILC) and paracetamol degradation, were taken from previous studies conducted by our research group Hurtado et al. (2019, 2022) [26,49]. The catalyst was only used in scenario 4. Samples were periodically collected to monitor the temporal evolution of paracetamol concentration and to determine the degree of mineralization achieved. For this purpose, liquid chromatography, and Total Organic Carbon (TOC) analyses were performed. The outputs modeled in the LCA included emissions to water, such as TOC, hydrogen peroxide, residual paracetamol, and acids; and air emissions to the stratosphere derived from residual H_2O_2.

Table 2. Life Cycle Inventory (LCI) of paracetamol degradation without treatment (Scenario 1) per functional unit. Treatment time: 120 min.

Scenario	Stage	Inputs		Unit	Outputs		Unit	Data Quality
1	Reaction	Paracetamol	0.10	g	TOC Paracetamol	0.064 0.10	g g	Experimental

Table 3. Life Cycle Inventory (LCI) of paracetamol degradation by photolysis (UV) treatment (Scenario 2) per functional unit. Treatment time: 120 min.

Scenario	Stage	Inputs		Unit	Outputs		Unit	Data Quality
2	Reaction	Paracetamol Energy	0.10 1.38	g kWh	TOC Paracetamol	0.063 0.050	g g	Experimental

Table 4. Life Cycle Inventory (LCI) of paracetamol degradation, UV+H_2O_2 treatment (Scenario 3) per functional unit. Treatment time: 120 min.

Scenario	Stage	Inputs		Unit	Outputs		Unit	Data Quality
3	Reaction	Paracetamol H_2O_2 Energy	0.10 0.483 1.38	g g kWh	TOC H_2O_2 Paracetamol	0.0256 0.338 0	g g g	Experimental

Table 5. Life Cycle Inventory (LCI) of catalyst synthesis and photo-Fenton process catalyzed by Cu/Fe PILC treatment (Scenario 4) per functional unit. Treatment time: 120 min.

Scenario	Stage	Inputs		Unit	Outputs		Unit	Data Quality
4	Catalyst synthesis	Energy	17.54	kWh	Cu/Fe-PILC	1	g	Experimental
		Bentonite	1	g				
		$FeCl_3 \cdot 6H_2O$	16.54	g				
		Cu $(CH_3COO)_2 \cdot H_2O$	1.01	g				
		Deionized water	2	L	Wastewater	2	L	
		NaOH	4.89	g				
		HCl (30%)	0.01	g				
	Reaction	Paracetamol	0.10	g	TOC	0.0115	g	Experimental
		Cu/Fe-PILC	0.5	g	Cu/Fe-PILC	0.5	g	
		H_2O_2	0.483	g	Paracetamol	0	g	
		H_2SO_4	0.001	L	H_2O_2	0	g	
		Energy	1.38	kWh	H_2SO_4	0.001	L	

2.3. Life Cycle Impact Assessment (LCIA)

The LCA was conducted using SimaPro PhD 10.2.0.2 software [50]. The database of inventory models for inputs was obtained from Ecoinvent 3.10 data as system processes [51]. Environmental impacts were quantified using two characterization methods: ReCiPe 2016 method (Midpoint V1.06/World (2010) H) [52] and USEtox™ [53]. These methodologies were applied to comprehensively associate the environmental burdens with both the synthesis of the studied catalysts [43] and the degradation process of paracetamol with CAS number (000103-90-2) [3].

The ReCiPe method was used to assess the environmental impacts of catalyst synthesis across 18 environmental categories: global warming (GW) (kgCO_2eq), stratospheric ozone depletion (SOD) (kg CFC_{11} eq), ionizing radiation (IR) (kBq Co-60 eq), ozone formation, human health (OfHh) (kg NOx eq), fine particulate matter formation (FPmf) (kg $PM_{2.5}$ eq), ozone formation, terrestrial ecosystems (OfTe) (kg NOx eq), terrestrial acidification (TA) (kg SO_2 eq), freshwater eutrophication (FE) (kg P eq), marine eutrophication (MA) (kg N eq), terrestrial ecotoxicity (TEc) (kg 1,4-DCB), freshwater ecotoxicity (FEc) (kg 1,4-DCB), marine ecotoxicity (MEc) (kg 1,4-DCB), human carcinogenic toxicity (HcT) (kg 1,4-DCB), human non-carcinogenic toxicity (HncT) (kg 1,4-DCB), land use (LU) (m^2a crop eq), mineral resource scarcity (MRs) (kg Cu eq), fossil resource scarcity (FRs) (kg oil eq) and water consumption (WC) (m^3) [52,54].

To assess toxicity related impacts in LCA, the USEtox™ model is widely recognized as the recommended consensus model for characterizing both human toxicity and freshwater ecotoxicity [3]. Developed through an international collaboration supported by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative, USEtox™ provides a scientifically robust framework for calculating CFs that account for the fate, exposure, and effects of chemical substances. These CFs allow for the quantification of potential impacts of emissions into various environmental compartments and are used to derive midpoint indicators, expressed as Comparative Toxic Units CTUh for human toxicity and CTUe for freshwater ecotoxicity. This enables consistent and comparative evaluations of chemical substances and treatment processes across life cycle stages [55].

In order to align USEtox™ CFs with the requirements of LCA, the model expresses human toxicity impacts as cumulative cases of either cancer or non-cancer health outcomes (cases per functional unit), and, for freshwater aquatic ecotoxicity impacts, as the potentially affected fraction (PAF) of aquatic species integrated over the exposed water volume (m^3), time (day) (PAF·m^3·day) [56]. Thus, the USEtox™ model employs Comparative Toxic Units for humans (CTUh), expressed as the estimated number of disease cases, and Comparative Toxic Units for ecosystems (CTUe), defined as the potentially affected fraction of species multiplied by the volume and time (PAF·m^3·day) [3].

The USEtox™ and ReCiPe methods were employed to quantify the environmental burden, specifically focusing on human toxicity (cancer and non-cancer) and freshwater ecotoxicity [57–59]. The application of both methods has also been reported by Moratalla et al. [2], who analyzed the environmental impacts of pharmaceutical ingredients such as paracetamol.

2.4. Interpretation

To complete the LCIA, a sensitivity analysis was conducted to assess how variations in pH affect the environmental performance of the photo-Fenton process. Specifically, the analysis compared two operational conditions 2.7 and 5.8 at different reaction time (10, 20, 60, 120 and 180 min), to assess how variations in acidity affect the overall environmental impacts associated with the Cu/Fe-PILC catalyzed treatment.

Considering that the generation of oxidizing species is more effective at acidic pH, as reported by Hurtado et al. [26], who observed a higher initial oxidation rate under acidic conditions (2.7) compared to circumneutral pH (5.8), it is relevant to evaluate both acidic and neutral pH levels. The effect of pH levels has been studied by Daniel et al. [60], who analyzed the combined impact of ocean acidification and paracetamol exposure. This approach allowed for the identification of trade-offs between treatment efficiency, chemical consumption, and environmental burden, providing insight into the robustness and optimization potential of the advanced oxidation process.

3. Results and Discussion

3.1. Life Cycle Impact Assessment of Catalyst Synthesis (Cu/Fe PILC)

This is a relevant analysis since the catalyst synthesis stage, albeit with other catalysts, has been reported with the highest damage in all categories [61]. Table 6 summarized the midpoint environmental impacts for the catalyst synthesis of 1 g of the Cu/Fe PILC catalyst. Among the 18 impact categories evaluated, energy consumption accounted for most of the environmental burden in 7 categories, whereas material inputs contributed significantly to only 4 categories. The material entry lists the environmental impacts due to the added reagents and materials. Reagents such as iron chloride ($FeCl_3 \cdot 6H_2O$), copper acetate ($Cu(CH_3COO)_2 \cdot H_2O$) and sodium hydroxide (NaOH), have an environmental contribution, mainly in the impact categories of Freshwater eutrophication (FEc), Marine eutrophication (Mec), human non carcinogenic toxicity (HncT) and Mineral resource scarcity (MRs). The energy consumption accounted for continuous stirring over 12 h, drying overnight at 75 °C and calcination at 400 °C for 2 h [26]. These findings are consistent with those reported by Costamagna et al. [62], particularly for impact categories such as climate change, ozone layer depletion, terrestrial acidification, and freshwater eutrophication.

Table 6. Midpoint environmental impact contributions associated with the synthesis of 1 g of Cu/Fe PILC catalyst.

Environmental Contribution	Impact Category		Unit
Energy	GW	10.98	kg CO_2 eq
	SOD	1.35×10^{-5}	kg CFC_{11} eq
	IR	0.53	kBq Co-60 eq
	TA	0.03	kg SO_2 eq
	OfHh	0.02	kg NO_x eq
	OfTe	0.02	kg NO_x eq
	FRs	3.54	kg oil eq
Material	FEc	0.03	kg 1,4-DCB
	Mec	0.04	kg 1,4-DCB
	HncT	0.50	kg 1,4-DCB
	MRs	1.53×10^{-3}	kg Cu eq

The GWP values obtained in this study were compared with those reported in other works related to the synthesis of copper or iron-based catalysts [63–68] (see Figure 3). It is worth emphasizing that the literature on this topic is rather scarce, and this work is the first effort to assess the environmental burdens of Cu/Fe PILC catalyst synthesis. Thus, data in Figure 3 must be analyzed with caution since they are not the same catalyst. In addition, other differences limiting a straightforward comparison are quality of data for the corresponding life cycle inventory. It also must be noted that source manuscripts for data in Figure 3, use different function units (FU) and therefore additional calculations were conducted to report data in the same FU (1 g) than this work.

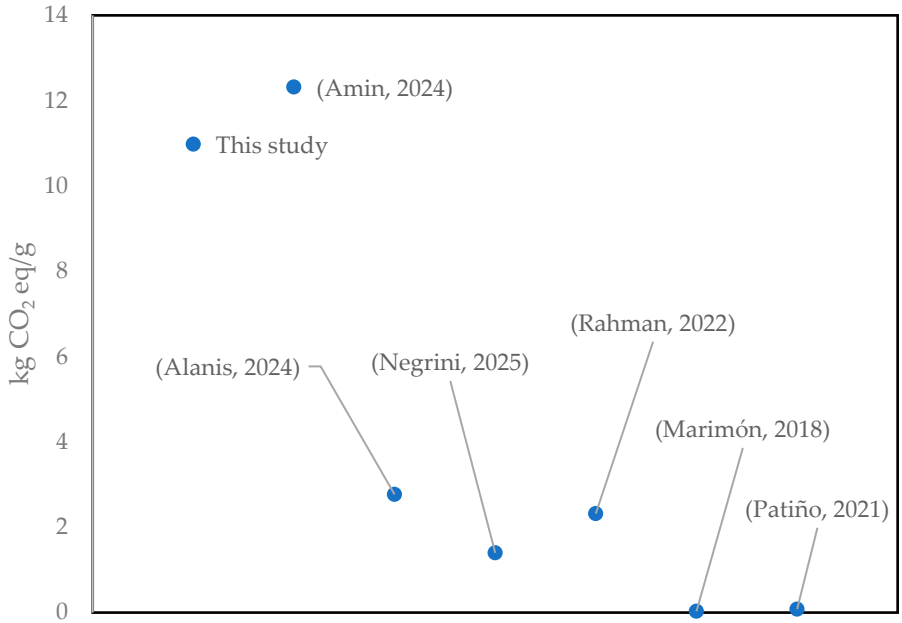


Figure 3. Average Global Warming Potential emissions of synthesis of copper or iron based heterogeneous catalysts (kg CO_2 eq). Functional unit: 1 g of catalyst. [63]:(Amin, 2024); [64]:(Alanis, 2024); [65]:(Rahman, 2022); [66]:(Negrini, 2025); [67]:(Marimón, 2018); [68]:(Patiño, 2021).

As shown in Figure 3, GWP values range between 0.03 [67] and 12.32 kg CO_2 eq/g. It must be pointed out, however, that the value reported by Rahman et al. [65] is based on calculations of cumulative energy demand using CED method and ecoinvent 3.6 database in SimaPro, while this study uses experimental data for energy demand calculations. In works where very low GWP values are reported, like [67,68], these are related to green catalyst synthesis where the calcination stage is not necessary to obtain the iron oxides. There is not doubt on the green characteristic of such processes; nevertheless, the application of such catalysts to photo-Fenton processes has not been assessed and the reusability of such catalysts must not be overlooked since the lack of calcination might lead to catalyst deactivation by leaching of the iron oxides.

The results in Figure 3 highlight the importance of optimizing the Cu/Fe PILC catalyst synthesis stage and this should be the aim of future research under more realistic production conditions, where large-scale synthesis may offer economies of scale that reduce overall impacts and energy requirements. A strategy that surely would decrease the GWP, as in other reported catalyst synthesis [69–72] is the use of renewable sources of energy instead of only fossil-based energy. In this sense, the environmental performance of catalyst production is also strongly conditioned by the energy matrix of each country [73]. For instance, regions highly dependent on fossil-based energy sources will inherently report higher greenhouse gas emissions in energy-intensive synthesis processes, compared to countries with cleaner or renewable-based energy grids. Expanding LCA research in this area would therefore provide a more comprehensive understanding of the variability in environmental outcomes and support the development of context-specific strategies to minimize impacts. Such studies could guide the design of sustainable synthesis pathways by integrating technological innovation with regional energy policies, ultimately contributing to the overall sustainability of catalytic systems [74].

3.2. Life Cycle Impact Assessment (LCIA) of Paracetamol Degradation

For the analysis of the environmental impacts associated with paracetamol removal, energy consumption was excluded in a similar way as in [75]. This decision was based on the specific objective of the study: to assess the potential toxicity-related impacts of

paracetamol removal and disposal using the USEtox™ method. The analysis focused exclusively on three impact categories human toxicity cancer, human toxicity non-cancer, and freshwater ecotoxicity [53], which are directly linked to emissions of chemical substances, rather than to operational energy use. Including energy consumption would have introduced additional variables beyond the scope of this targeted toxicological assessment.

Characterization factors (CFs) play a crucial role in the LCIA phase of LCA by quantifying potential human and ecological impacts of chemical emissions [3]. CFs, especially relevant in toxicity-related categories, integrate fate, exposure, and effect components [76], based on environmental modeling and toxicological data [77].

In general, LCA applied to wastewater treatment via Fenton-based processes has identified energy use and chemical consumption as the primary contributors to environmental burdens. Notably, energy was reported as the main environmental hotspot in 77% of studies involving conventional homogeneous Fenton processes and in 42% of studies addressing hybrid and heterogeneous Fenton systems [43].

3.2.1. Human Toxicity Cancer

This impact refers to the estimated number of potential human disease cases (cancer) per kilogram of substance emitted. Environmental modeling considers contaminants persistence in the environment, its potential for bioaccumulation, and its toxicity to humans [56]. In this work, scenario S4 showed the highest environmental impact value by the photo-Fenton process (photo-Fenton catalyzed by Cu/Fe PILC); followed by S1, where the paracetamol solution is discharged without any treatment; then scenario S2, where the paracetamol solution was only treated by UV-light (photolysis); and finally, S3, where the paracetamol solution was treated by UV light and hydrogen peroxide was also added (UV-H_2O_2). The contribution percentage of each scenario was: S1:93.07%, S2:46.54% and S3:27.09%, as shown in Figure 4. The units corresponding to each treatment scenario are presented in Table 7. The human toxicity cancer of S4 was 9.73 $\times 10^{-12}$ CTUh (comparative toxic units for humans), corresponding to the potential occurrence of 9.73 $\times$ 10^{-12} cancer cases per kilogram of emissions. Thus, this extremely low value reflects the minimal carcinogenic risk associated with the process, particularly under the tested conditions and operational parameters. Thus, the results suggest that the application of the Cu/Fe-PILC photo-Fenton system poses negligible concern in terms of human cancer toxicity, likely due to the effective degradation of paracetamol and the low persistence and toxicity of residual chemicals in the treated effluent.

Table 7. Environmental impacts of treatment scenarios for paracetamol degradation per functional unit. Treatment time: 120 min.

Impact Category	Unit	S1 (Without Treatment)	S2 (Photolysis)	S3 (UV + H_2O_2)	S4 (Photo-Fenton Cu/Fe PILC)
Human toxicity, cancer	CTUh	9.06×10^{-12}	4.53×10^{-12}	2.69×10^{-12}	9.73×10^{-12}
Human toxicity, non-cancer	CTUh	0	0	3.67×10^{-14}	1.29×10^{-13}
Freshwater ecotoxicity	PAF·m^3·day	8.66×10^{-3}	4.33×10^{-3}	1.67×10^{-4}	5.70×10^{-4}

For Scenario 1, i.e., discharging paracetamol without treatment, the human toxicity cancer was calculated as 9.06×10^{-12} CTUh. Therefore, it can also be concluded that from the perspective of human carcinogenic toxicity, paracetamol poses no significant effects. Moratalla et al. [2] reported a negligible value of 4.53×10^{-10} cases in hospital wastewater. Thus, in the context of carcinogenic toxicity, the presence of paracetamol in water does not

pose a risk to human health and this is in concordance with other works [78,79]. When used as directed, at therapeutic doses up to 4 g/day for adults, paracetamol is not classified as a carcinogenic hazard [80]. At these doses, only limited amounts of the toxic metabolite N-acetyl-p-benzoquinone-imine (NAPQI) are formed, without causing adverse cellular effects. Although NAPQI can induce mitochondrial dysfunction and Deoxyribonucleic Acid (DNA) damage, this occurs only at toxic doses that result in cell death [81].

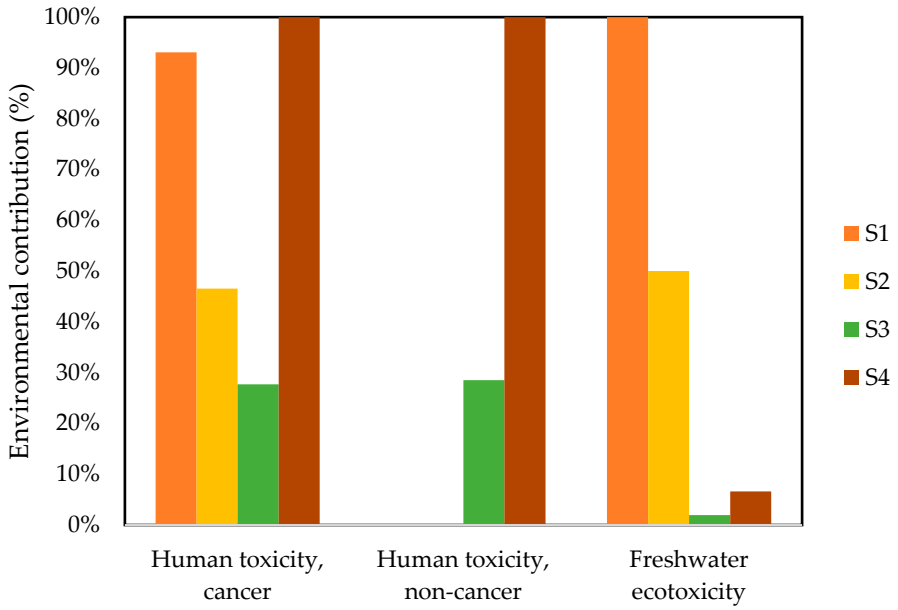


Figure 4. Environmental contribution treatment scenarios for paracetamol degradation: S1 (without treatment), S2 (Photolysis), S3 (UV-H_2O_2) and S4 (Photo Fenton process catalyzed with Cu/Fe PILC). Treatment time: 120 min.

3.2.2. Human Toxicity, Non-Cancer

The human toxicity, non-cancer impact category showed notable contributions in scenarios where strong chemical reagents were used, S3 and S4, particularly hydrogen peroxide (H_2O_2) and sulfuric acid (H_2SO_4), both of which have been previously reported as substances with potential human health concerns [43,82]. Foteinis et al. [83] quantified the impact category of global warming potential (2.71 kg CO_2 eq per m^3) of wastewater treated, from which 92.4% of these emissions were linked to chemical consumption. Among reagents, H_2O_2 (62.3%) and oxalic acid (14.6%) were identified as the main environmental hotspots of the treatment process.

In this category, scenarios S1 and S2 exhibited null impact values for non-carcinogenic human toxicity, attributable to the absence of emissions from the reagents used in the corresponding paracetamol degradation treatments. The results in Table 7 also indicate that disposing paracetamol without any treatment does not pose a risk for the category of Human toxicity, non-cancer.

The treatments with the greatest environmental contribution are S4 with 100% and S3 with 28.51% (see Figure 3). Under these conditions, the estimated human toxicity, non-cancer potential was 3.67×10^{-14} cases for scenario S3 and 1.29×10^{-13} cases for scenario S4. This indicates a higher non-carcinogenic toxicity burden in scenario S4, likely attributable to the combined use of H_2O_2 and acidification with H_2SO_4, both required for the catalytic photo-Fenton process. In scenario S4, sulfuric acid was used to maintain the required acidic conditions for the photo-Fenton reaction, specifically at pH 2.7, which enhances radical generation but also contributes to toxicity-related impacts due to the handling and production of such chemicals. Although the heterogeneous Fenton

system eliminates the need for continuous catalyst dosing observed in the homogeneous systems, it demands a great quantity of H_2O_2 to achieve similar total organic carbon (TOC) removal efficiencies. This trade-off highlights the importance of evaluating both the environmental and operational implications of reagent use when selecting advanced treatment technologies and this is in concordance with that previously reported [43].

3.2.3. Freshwater Ecotoxicity

This indicator quantifies the potential risk to aquatic ecosystems resulting from exposure to toxic compounds released during the treatment process [3,53,84]. Urban wastewater, along with effluents from pharmaceutical manufacturing, can ultimately reach surface water bodies. Due to its widespread use, paracetamol is considered one of the most prevalent emerging contaminants [85]. Even at low environmental concentrations, it has been shown to exhibit toxic effects on aquatic organisms, including endocrine-disrupting activity in certain fish species [3,86]. In some crustaceans, environmental levels of paracetamol have been associated with increased mortality resulting from development of abnormalities and alterations in sex hormone regulation [87]. Evaluating freshwater ecotoxicity is therefore crucial for understanding and mitigating the risks posed to aquatic life and maintaining the ecological balance of affected water bodies [9,22]. Paracetamol toxicity may vary due to unpredictable physiological factors, which can hinder accurate extrapolations and comparisons of responses across different species [86]. In this sense and according to [86], the proportion of species affected by acute exposure to paracetamol increases in the following order *D. magna* < *D. longispina* < *V. fischeri* < *C. raciborskii* < *P. subcapitata* < *L. minor*.

In this impact category, scenarios S1 and S2, exhibited the highest environmental contributions (see Figure 4), primarily due to the presence of untreated or partially degraded paracetamol and the use of chemical reagents with ecotoxic potential. In contrast, scenario S3, 98.02%, and S4 resulted in a 93.42% reduction in freshwater ecotoxicity compared to the other scenarios, as shown in Figure 4. This significant improvement is attributed to the enhanced degradation efficiency of paracetamol under catalytic photo-Fenton conditions (pH 2.7 at 120 min), which minimizes the concentration of harmful intermediates and residual contaminants in the effluent. The impact unit for S4 was 5.70×10^{-4} PAF·m^3·day. This can be attributed to the unreacted hydrogen peroxide accounted as an output (see Table 1). In concordance with this, Ribeiro et al. [43] concluded that the highest impact scores associated with freshwater toxicity, were primarily due to the use of chemical reagents particularly H_2O_2.

Moratalla et al. [2] reported a negligible value of 3.16×10^{-4} PAF·m^3·day as a functional unit per 0.01 mg dm^{-3} for each drug in 500 m^3 in hospital wastewater. Thus, the reported values in Table 7 for all scenarios can also be considered negligible. Nevertheless, S4 implies a reduction of one order of magnitude compared to disposing of paracetamol without any treatment (S1).

In the context of Fenton process, production of chemicals has been regarded as the second-most cited contributor to the environmental footprint of the process [43]. Thus, the input of any chemical to the process will importantly contribute to its environmental footprint. For this work, Figure 5 depicts the contribution percentage to mid-point level environmental categories, of hydrogen peroxide and sulfuric acid addition to the photo-Fenton process. Contrary to that reported by [43], it can be observed in Figure 5 that H_2O_2 is not the main contributor to all environmental impacts, while H_2SO_4 impacts most of them. From the eighteen assessed environmental categories, there are only six where the hydrogen peroxide is the main contributor, i.e., WC, FRs, HcT, ME, IR and GW. The relative high contribution to most of these categories can be ascribed to the reported high energy consumption by H_2O_2 production (1200 kWh·kg^{-1} of H_2O_2). Regarding HcT, this

category might be highly impacted since H_2O_2 production involves anthraquinone and a mix of alkyl-aromatic solvents [88]. It is worth noticing that the environmental footprint of chemical addition is not only due to its production but is also related to the amount added. In this sense, it is important to notice that the H_2O_2 concentration used in each Fenton process varies and it is usually one or two orders of magnitude higher than the stoichiometrically required. The process analyzed in this work was added only with the stoichiometric amount, i.e., 0.483 g, and this might also be the reason for H_2O_2 not being the main environmental footprint contributor as in other Fenton-related works [43].

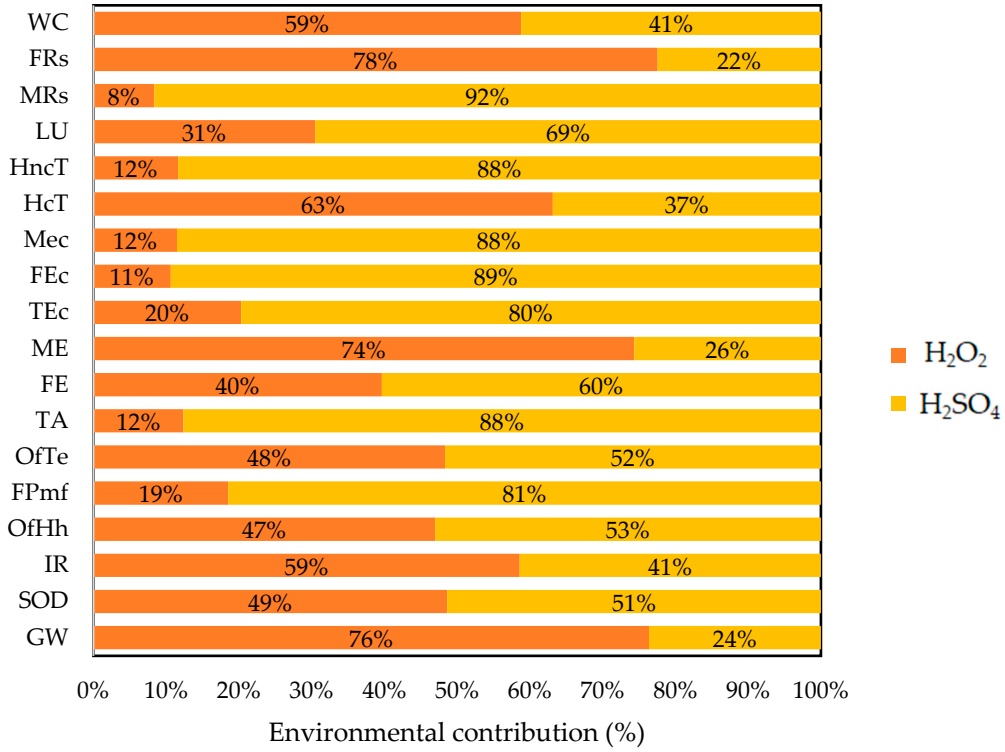


Figure 5. Contribution percentage to mid-point level environmental categories of hydrogen peroxide and sulfuric acid addition to the photo-Fenton process.

Figure 5 shows that sulfuric acid contribution is higher than hydrogen peroxide in the FEc environmental category. This suggests then that the addition of sulfuric acid, considered as an input and output in the photo-Fenton process inventory, is the main reason for the slightly higher contribution percentage to this category by Scenario 4 than Scenario 3 observed in Figure 4. This can be concluded because the other plausible chemical contributors like paracetamol, oxidation intermediates or carboxylic acids are considerably lower in S4 than in S3, as per reported by [26] and indicated in the LCI, Tables 4 and 5. This result also serves to justify the study of pH effect on the overall treatment efficiency and a sensitivity analysis on this parameter.

3.3. Sensitivity Analysis

The photo-Fenton process efficiency with a heterogeneous catalyst like the one in this work, i.e., Cu/Fe-PILC, relies on the catalyst and on other reaction conditions like catalyst dose and pH [89]. Through various works, it has been demonstrated that the organic compounds removal rate is higher when the photo-Fenton process is conducted at acidic pH, although the achieved removal extent is very similar [26]. This has raised the question about the worthiness of conducting the photo-Fenton process under acidic or circumneutral pH [38]. The former requires the addition of reagents like sulfuric acid to

decrease the initial pH solution, while the latter does not demand any additional reagent. As shown in Figure 6, the addition of sulfuric acid represents an important environmental burden because of its manufacturing. The work of Novoa et al. [90] already demonstrated that even when mineralization was higher at acidic pH than at natural pH, the toxicity on *Hyalella azteca* was eliminated when the treatment was conducted under natural pH (pH = 8). Therefore, a sensitivity analysis was conducted to assess the influence of pH by comparing the contributions to environmental impact categories of the photo-Fenton process at acidic (pH 2.7) and natural pH (pH 5.8). The scenario of nil treatment was also assessed, i.e., a paracetamol containing effluent being discharged without any treatment to remove paracetamol.

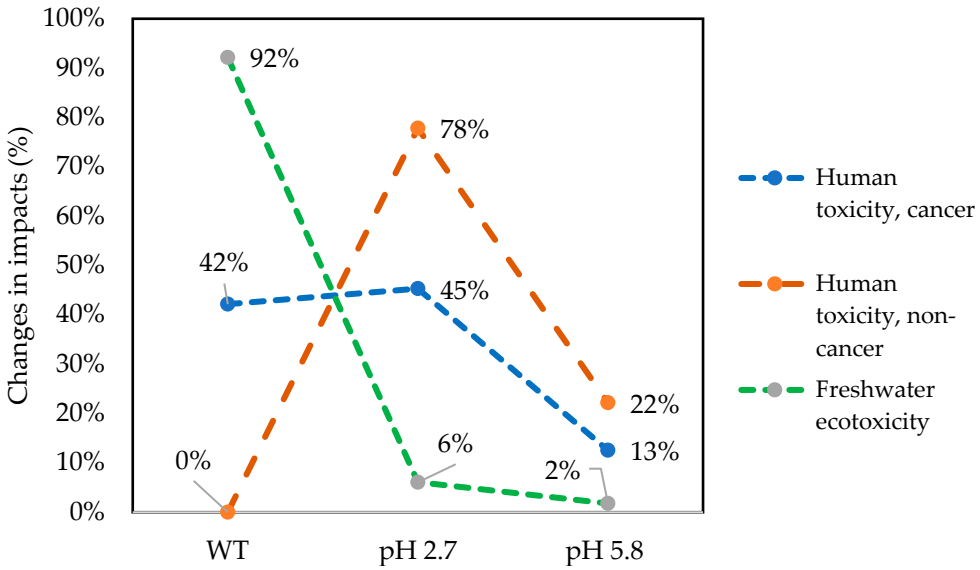


Figure 6. Effect of nil treatment (Scenario 1) and pH (2.7 and 5.8) of the photo-Fenton process catalyzed by Cu/Fe-PILC for paracetamol degradation (Scenario 4), on the contribution to long term environmental categories. Treatment time: 120 min.

Figure 6 shows the effect of conducting the photo-Fenton process at two different pH, 2.7 and 5.8, on contribution to long term environmental categories. There is also in Figure 6 included the contribution of the scenario when the paracetamol containing effluent is discharged without any treatment (WT). In Figure 6, it can be observed in that Freshwater ecotoxicity is the impact category with the most significant change, from 92 to 2%. This important change is due to the final emissions such as TOC (Total Organic Carbon) and acetaminophen implying a risk to aquatic ecosystems due to exposure to pollutants. It is worth pointing out that this change was observed thanks to the use of USEtox™, otherwise, by applying Recipe method, the impact on this category was not plausible.

In Figure 6, the human toxicity, non-cancer category is observed to be nil when there is no treatment (Scenario 1). The contribution to this environmental category is increased to 78 and 22%, by the photo-Fenton process initially conducted at pH = 2.7 and 5.8, respectively. In the first case, this increase can be ascribed mainly to the non-carcinogenic adverse effects (reproductive, neurological, respiratory, etc.) of H_2SO_4 added to the process starting at pH 2.7. The primary environmental concerns associated with the use of H_2SO_4 for pH adjustment in wastewater treatment are also related to the emission of acid rain precursors and the reliance on metallic materials such as catalysts required for its industrial production [91]. When the initial pH is 5.8, the increase is only 22% with respect to the Scenario 1 (without treatment), and this can be ascribed to not adding sulfuric acid, since the paracetamol concentration and TOC at the end of treatment are very similar to

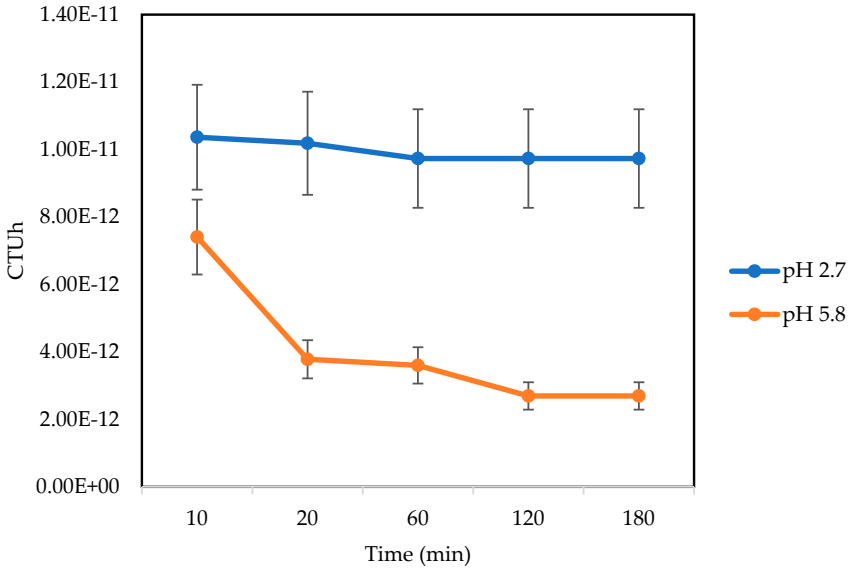
those reported at acidic pH. Nevertheless, the magnitude of the environmental impacts of the photo-Fenton process are 1.29×10^{-13} cases and 3.67×10^{-14} cases, respectively; these are considered negligible in the context of human toxicity, non-cancer.

Regarding the environmental category human toxicity, cancer; there were included all final emissions, carcinogenesis-related impacts and it can be observed in Figure 6 that the contribution to this category decreased from 45% to ca. 13%, with the photo-Fenton treatment conducted at pH of 5.8.

Thus, based on the sensitivity analysis, it can be concluded that from the assessed scenarios in Figure 6, the less harmful for the long-term environmental categories, i.e., human nontoxicity, cancer; human toxicity, cancer and freshwater toxicity, is the photo-Fenton process conducted under an initial circumneutral pH of 5.8.

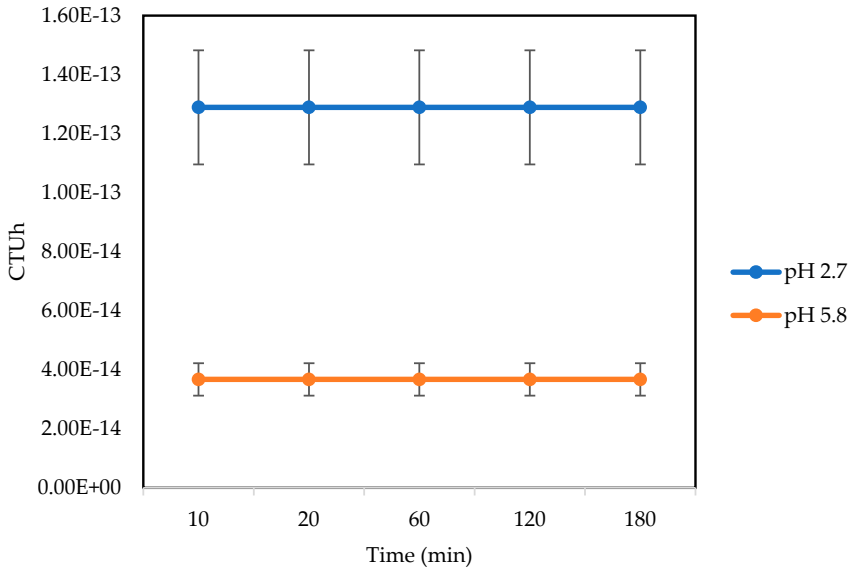
The effect of treatment time (10, 20, 60, 120 and 180 min) was assessed on the long-term impact categories of the paracetamol degradation by photo-Fenton Cu/Fe PILC at both pH, 2.7 and 5.8. Error bars corresponding to a 15 % uncertainty were included to reflect variability in the measurements and to provide a more robust interpretation of results. In Figure 7a, it is observed that the impact category of HcT, at a pH of 5.7 and 180 min, is 2.69×10^{-12} cases, while at pH 2.7 at 60 min, the value no longer changes from 9.73×10^{-12} cases. In Figure 7b, the HncT impact category, at pH 2.7, does not change (1.29×10^{-13} cases), as well as at pH 5.8, 3.67–14 cases remain constant, being a non-sensitive category. In Figure 7c, the FEc impact category, at pH 2.7, the value no longer changes from minute 60, 5.70×10^{-4} PAF·m^3·day; while at pH 5.8, the impact finds a minimum at 120 min of treatment, 1.67×10^{-4} PAF·m^3·day, which is about 3 times lower than that observed for the process conducted at acid pH. The observed trend for circumneutral pH can be ascribed to paracetamol removal and hydrogen peroxide consumption rate, both being faster in the process conducted at acid pH. Nevertheless, the low value observed after 120 min of treatment can be ascribed to the fact of sulfuric acid not being added to the process and therefore not being an output, as well as achieving similar paracetamol and TOC outputs than the process at a pH = 2.7.

Thus, because of the above discussed, it can be concluded that the most sensitive impact category during reaction time was that of FEc, at a pH of 5.8, since it decreased by up to 96%. The sensitivity to pH has been previously reported by Morais et al. [77].

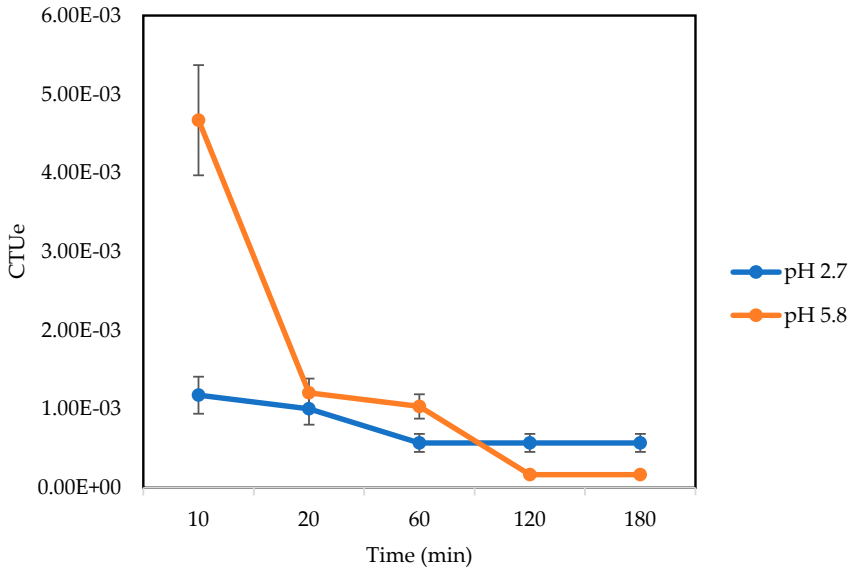


(**a**) Human carcinogenic toxicity

Figure 6. *Cont.*



(**b**) Human non-carcinogenic toxicity



(**c**) Freshwater ecotoxicity

Figure 7. Evaluation of impact categories for the Photo-Fenton process catalyzed with Cu/Fe-PILC at pH 2.7 and 5.8 (scenario 4), across different reaction times: (**a**) Human carcinogenic toxicity, (**b**) Human non-carcinogenic toxicity and (**c**) Freshwater ecotoxicity. Comparative Toxic Units for humans (CTUh), expressed as the estimated number of disease cases per kilogram of substance emitted. Comparative Toxic Units for ecosystems (CTUe), defined as the potentially affected fraction of species multiplied by the volume and time (PAF·m^3·day).

3.4. Photo-Fenton Process to Remove Paracetamol: A Perspective

In Figure 8, the freshwater ecotoxicity values obtained in this study were compared with those reported in other works on Advanced Wastewater Treatment for removal of pharmaceuticals for an equivalent functional unit (L) with ReciPe2016 and USEtox methods [75,92,93]. It is worth noting that no works related to the assessment of paracetamol removal with USEtox were found in the literature. Thus, it must be borne in mind that data presented in Figure 8 are from works dealing with treatment of effluents of complex composition in wastewater treatment plants. Nevertheless, Figure 8 aims to position the results regarding FE from this work in the context of AOP applied to pharmaceuticals

removal. As shown, FE values range between 5.70×10^{-4} and 2.10×10^{-2} PAF·m^3·day. Zepon et al. [75] reported a solar photo-Fenton at low pH excluding electricity consumption to remove pharmaceuticals and personal care products. For a similar effluent, Li et al. [92] evaluated a reverse osmosis process, which was identified as the most environmentally intensive scenario among ozonation and granular activated carbon adsorption due to its high electricity and chemical consumption. Surra et al. [93] studied an electrochemical process with Boron-Doped Diamond (BDD) electrodes, mainly due to the indirect environmental burdens associated with the production of electric energy used and to the anodes' manufacturing. Indeed, variations in electricity consumption across these advanced wastewater treatment processes were found to exert the most pronounced influence on the overall LCA outcomes. These works also highlight the importance of assessing the environmental burdens of advanced oxidation processes.

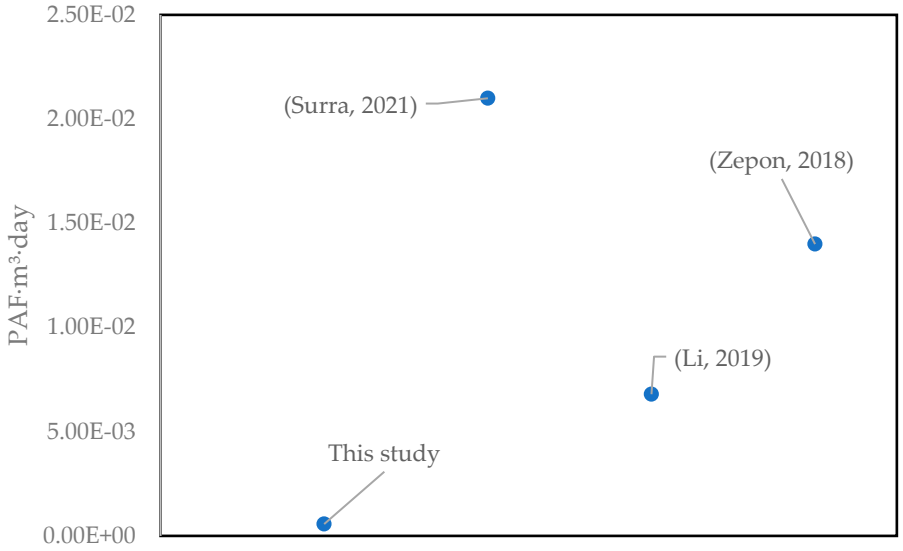


Figure 8. Average of Freshwater ecotoxicity of Advanced Wastewater Treatment for removal of pharmaceuticals (PAF·m^3·day). Functional Unit: 1 L. [75]:(Zepon, 2018); [92]:(Li, 2019); [93]:(Surra, 2021).

The Freshwater ecotoxicity calculated in this work is ascribed to the considered emissions like total organic carbon, unreacted hydrogen peroxide (zero for photo-Fenton) and sulfuric acid (only for a pH of 2.7). LCA of wastewater treatment technologies based on TOC is a common practice [42] since this parameter accounts for all the remaining organic material. From a toxicological point of view, this might be a limiting consideration of this, and other works based solely on TOC emissions. This statement is further elaborated upon below.

Figure 9 depicts a general scheme to produce hydroxyl radicals via photo-Fenton process catalyzed with Cu/Fe-PILC (S4), via photodecomposition of hydrogen peroxide (S3) and via photocatalysis (oxidation of water on the positive charged holes in the valence band, h^+). All the identified oxides on the prepared catalyst, i.e., CuO, Cu_2O, Fe_3O_4 and FeO, are semiconductors with a calculated band-gap energy of ca. 2.08 eV [94]. This characteristic makes it possible that radiation with wavelength in the UV and in the visible region manages to excite an electron from the valence band (*vb*) to the conduction band (*cb*), leaving behind positive charged holes, h^+, and promoting the electron transfer to hydrogen peroxide to produce hydroxyl radicals, $^{\bullet}$OH.

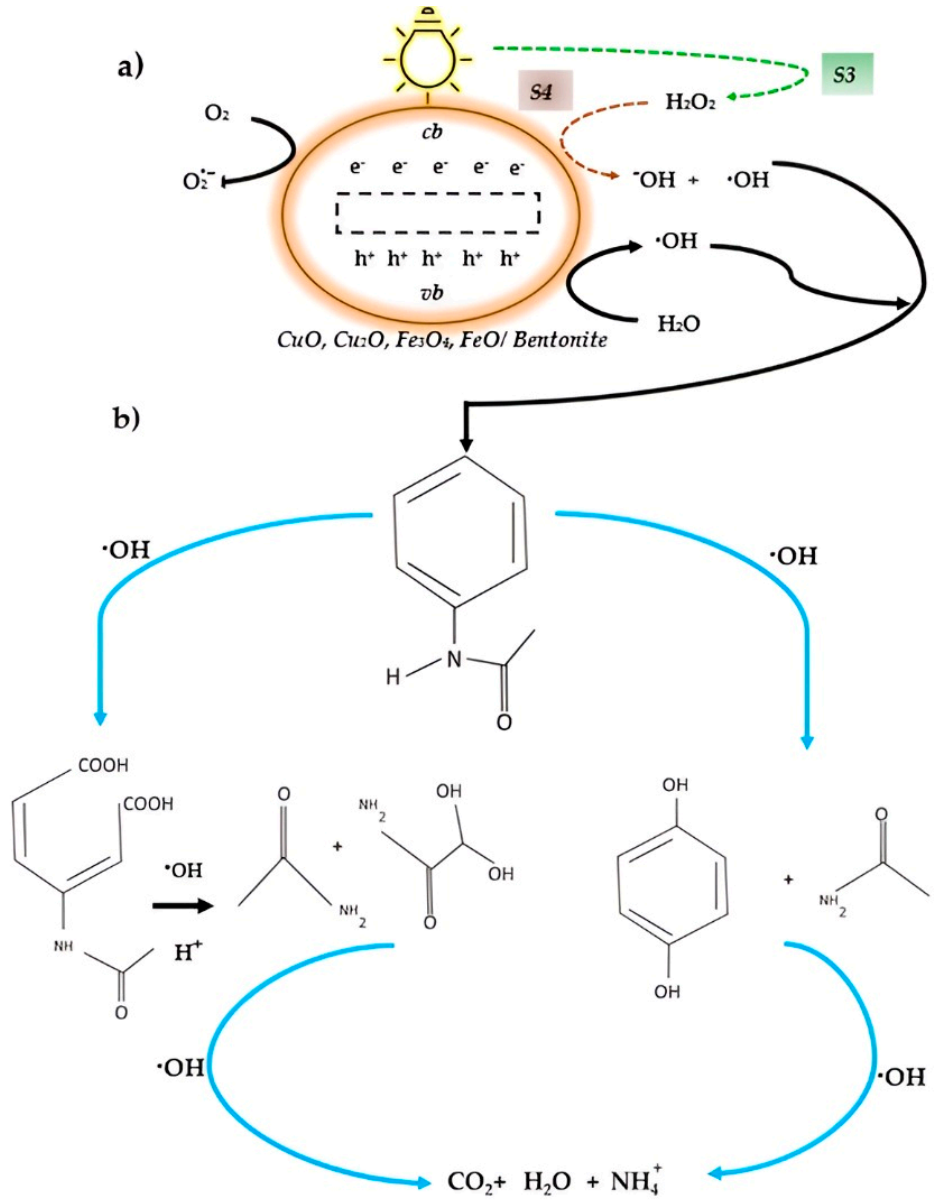


Figure 9. Scheme for the generation of hydroxyl radicals in the photo-Fenton process (**a**) and plausible paracetamol oxidation pathway via these radicals (**b**). Based on [26].

Based on the identified by-products in [26], i.e., hydroquinone, acetamide and oxamic acid, it was postulated by [26] that paracetamol oxidation via hydroxyl radicals (HR) might follow two plausible routes depicted in Figure 9b. In one of them, HR leads to the hydroxylation of the aromatic ring and a muconic type cleavage is observed due to an excess of HR and in the other plausible oxidation route, HR is added to the aromatic ring and hydroquinone and acetamide are produced. According to the results reported by [26], the concentration of these chemical intermediates changes with time and with pH. After 120 min, the remaining TOC was attributed to the presence of acetamide, oxamic acid and hydroquinone. As depicted in Figure 9b, other emissions are also expected like CO_2 in water and ammonium ions. These inorganic species were not quantified in the source manuscript for this work. Such quantification is important not only in this work but in all studies related to advanced oxidation processes, both from a toxicological point of view and to assess the feasibility of using the residues as feedstock to produce fuels such as hydrogen or formic acid [95].

From the perspective of advanced oxidation processes, the application of photo-Fenton processes catalyzed by Cu/Fe-pillared clay (Cu/Fe-PILC) for paracetamol removal offers several advantages, like a high TOC removal percentage and total paracetamol removal. The process, however, is associated with high energy consumption, particularly for UV-light-driven operations and this concurs with other works [96,97]. Because of its reported band-gap energy, the use of Cu/Fe-pillared clay might allow its outdoor application, and this deserves further research. From a LCA perspective, however, future research on heterogeneous photo-Fenton processes should prioritize the use of renewable energy sources to reduce environmental and operational impacts [98–100], solar-driven photo-Fenton is the most environmentally friendly alternative, mainly because the use of electricity in solar photoelectro-Fenton experiments involves high environmental impacts. Among these, solar-driven photo-Fenton represents the most environmentally sustainable option, as conventional electricity-driven photoelectro-Fenton experiments are associated with significantly higher environmental burdens [42]. As well as the investigation of visible-light-responsive catalysts to broaden applicability beyond UV-dependent systems.

Optimization of catalyst dose, H_2O_2 and H_2SO_4 dosages is also necessary to enhance process efficiency and its sustainability. Scaling up to pilot or industrial levels will be essential to evaluate real-world performance and operational feasibility. Additionally, exploring catalyst recyclability and recovery is a key step to improve sustainability, minimize waste generation, and reduce costs. Importantly, although heterogeneous photo-Fenton processes are considered effective due to their broad operational pH range and catalyst reusability, the design and development of highly efficient heterogeneous catalysts remain a major challenge that must be addressed to advance their large-scale application.

Despite their relevance, LCAs focused on the synthesis stage of catalysts remain scarce in the current literature, representing a significant area of opportunity for further investigation. Particularly in the case of the catalyst used here, an optimization process of the catalyst synthesis stage must be conducted.

4. Conclusions

A life cycle assessment was conducted by the first time of four scenarios to remove paracetamol: without treatment, photolysis, hydrogen peroxide photo-decomposition and photo-Fenton catalyzed by Cu/Fe-PILC.

The synthesis of the catalyst was also assessed and the main contribution to the 18 mid-term environmental impacts was found to be energy consumption due to the stirring and oven to calcine the catalyst. This implies a necessity to decrease energy consumption in this stage by optimizing every step and integrating renewable energy, at least in some percentage.

The application of the Cu/Fe-PILC photo-Fenton system poses negligible concern in terms of human cancer and non-cancer toxicity. The calculated values were 9.73×10^{-12} CTUh and 1.29×10^{-13} CTUh, respectively. The use of sulfuric acid, however, to keep an acid pH, contributes to toxicity-related impacts due to the handling and production of such chemicals, and to the environmental impact of freshwater ecotoxicity. To decrease this impact, pH and treatment time must be optimized. Freshwater ecotoxicity is the environmental impact that must be used to assess paracetamol removal technology.

The results indicate that operating the photo-Fenton process under near-neutral pH conditions could be a viable alternative from an environmental perspective, as it reduces the need for acidification and neutralization steps. This leads to lower impacts associated with reagent use and energy requirements. Although oxidative efficiency was slightly lower under neutral conditions, the difference in mineralization was minimal, reinforcing the practical potential of this approach for real-world applications.

This study might be limited because it was conducted at laboratory scale and did not consider energy consumption in any scenario for paracetamol removal. Future research should aim to optimize the dosage of hydrogen peroxide and sulfuric acid to improve process efficiency under more sustainable conditions. Additionally, efforts should be directed toward evaluating the system's performance in pilot-scale applications for the management and treatment of hospital effluents, incorporating real operational variables.

Finally, an expanded life cycle assessment integrating social and economic dimensions is recommended to provide a more comprehensive evaluation of the process sustainability.

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Abbreviations

The following abbreviations are used in this manuscript:

AOPs	advanced oxidation processes
CFs	characterization factors
COD	chemical oxygen demand
CTUe	Comparative Toxic Units for ecosystems
CTUh	Comparative Toxic Units for humans
DNA	Deoxyribonucleic Acid
FE	freshwater eutrophication
FEc	freshwater ecotoxicity
FPmf	fine particulate matter formation
FRs	fossil resource scarcity
GW	global warming
HR	Hydroxyl Radical
H_2O_2	hydrogen peroxide
H_2SO_4	Sulfuric acid
HcT	human carcinogenic toxicity
HncT	human non-carcinogenic toxicity
IR	ionizing radiation
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LU	land use
MA	marine eutrophication

MEc	marine ecotoxicity
MRs	mineral resource scarcity
NAPQI	N-acetyl-p-benzoquinone-imine
OfHh	ozone formation, human health +
OfTe	ozone formation, terrestrial ecosystems
OH	hydroxyl radicals
PAF	potentially affected fraction
PILCs	pillared clays
S1	Scenario 1, paracetamol solution is discharged without treatment
S2	Scenario 2, paracetamol solution is treated by photolysis prior being discharged
S3	Scenario 3, paracetamol solution is treated by photodecomposition of hydrogen peroxide prior being discharged
S4	Scenario 4, paracetamol solution is treated by photo-Fenton prior being discharged
SETAC	Society of Environmental Toxicology and Chemistry
SOD	stratospheric ozone depletion
TA	terrestrial acidification
Tec	terrestrial ecotoxicity
TOC	Total Organic Carbon
UNEP	United Nations Environment Programme
WC	water consumption
WWTPs	wastewater treatment plants

References

1. Igos, E.; Benetto, E.; Venditti, S.; Köhler, C.; Cornelissen, A. Comparative and Integrative Environmental Assessment of Advanced Wastewater Treatment Processes Based on an Average Removal of Pharmaceuticals. *Water Sci. Technol.* **2013**, *67*, 387–394. [CrossRef]
2. Moratalla, Á.; Cotillas, S.; Lacasa, E.; Fernández-Marchante, C.M.; Ruiz, S.; Valladolid, A.; Cañizares, P.; Rodrigo, M.A.; Sáez, C. Occurrence and Toxicity Impact of Pharmaceuticals in Hospital Effluents: Simulation Based on a Case of Study. *Process Saf. Environ. Prot.* **2022**, *168*, 10–21. [CrossRef]
3. Ortiz de García, S.; García-Encina, P.A.; Irusta-Mata, R. The Potential Ecotoxicological Impact of Pharmaceutical and Personal Care Products on Humans and Freshwater, Based on USEtoxTM Characterization Factors. A Spanish Case Study of Toxicity Impact Scores. *Sci. Total Environ.* **2017**, *609*, 429–445. [CrossRef] [PubMed]
4. Chen, Z.; Lian, J.Z.; Zhu, H.; Zhang, J.; Zhang, Y.; Xiang, X.; Huang, D.; Tjokro, K.; Barbarossa, V.; Cucurachi, S.; et al. Application of Life Cycle Assessment in the Pharmaceutical Industry: A Critical Review. *J. Clean. Prod.* **2024**, *459*, 142550. [CrossRef]
5. Lindqvist, N.; Tuhkanen, T.; Kronberg, L. Occurrence of Acidic Pharmaceuticals in Raw and Treated Sewages and in Receiving Waters. *Water Res.* **2005**, *39*, 2219–2228. [CrossRef] [PubMed]
6. McCudden, C. Analgesics and Anti-Inflammatory Drugs. In *Toxicology Cases for the Clinical and Forensic Laboratory*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 67–74.
7. Fent, K.; Weston, A.; Caminada, D. Ecotoxicology of Human Pharmaceuticals. *Aquat. Toxicol.* **2006**, *76*, 122–159. [CrossRef]
8. Yadav, D.; Banerjee, R. Net Energy and Carbon Footprint Analysis of Solar Hydrogen Production from the High-Temperature Electrolysis Process. *Appl. Energy* **2020**, *262*, 114503. [CrossRef]
9. Gleneadie, H.J.; Baker, A.H.; Batis, N.; Bryant, J.; Jiang, Y.; Clokie, S.J.H.; Mehanna, H.; Garcia, P.; Gendoo, D.M.A.; Roberts, S.; et al. The Anti-Tumour Activity of DNA Methylation Inhibitor 5-Aza-2′-Deoxycytidine Is Enhanced by the Common Analgesic Paracetamol through Induction of Oxidative Stress. *Cancer Lett.* **2021**, *501*, 172–186. [CrossRef]
10. Grandclément, C.; Seyssiecq, I.; Piram, A.; Wong-Wah-Chung, P.; Vanot, G.; Tiliacos, N.; Roche, N.; Doumenq, P. From the Conventional Biological Wastewater Treatment to Hybrid Processes, the Evaluation of Organic Micropollutant Removal: A Review. *Water Res.* **2017**, *111*, 297–317. [CrossRef]
11. Pirvu, F.; Covaliu-Mierlă, C.I.; Catrina, G.A. Removal of Acetaminophen Drug from Wastewater by Fe_3O_4 and ZSM-5 Materials. *Nanomaterials* **2023**, *13*, 1745. [CrossRef]
12. Jang, D.; Jeong, S.; Jang, A.; Kang, S. Relating Solute Properties of Contaminants of Emerging Concern and Their Rejection by Forward Osmosis Membrane. *Sci. Total Environ.* **2018**, *639*, 673–678. [CrossRef]
13. Lee, W.J.; Goh, P.S.; Lau, W.J.; Wong, K.C.; Suzaimi, N.D.; Ismail, A.F. Tailoring the Permeability and Flux Stability of Forward Osmosis Membrane with Tert-Butylamine Functionalized Carbon Nanotubes for Paracetamol Removal. *J. Environ. Chem. Eng.* **2022**, *10*, 107977. [CrossRef]

14. Yin, C.-F.; Pan, P.; Li, T.; Song, X.; Xu, Y.; Zhou, N.-Y. The Universal Accumulation of P-Aminophenol during the Microbial Degradation of Analgesic and Antipyretic Acetaminophen in WWTPs: A Novel Metagenomic Perspective. *Microbiome* **2025**, *13*, 68. [CrossRef]
15. Kounaris Fuziki, M.E.; Ribas, L.S.; Tusset, A.M.; Brackmann, R.; Dos Santos, O.A.A.; Lenzi, G.G. Pharmaceutical Compounds Photolysis: PH Influence. *Heliyon* **2023**, *9*, e13678. [CrossRef]
16. Giménez, B.N.; Conte, L.O.; Duarte, S.A.; Schenone, A.V. Improvement of Ferrioxalate Assisted Fenton and Photo-Fenton Processes for Paracetamol Degradation by Hydrogen Peroxide Dosage. *Environ. Sci. Pollut. Res.* **2024**, *31*, 13489–13500. [CrossRef]
17. Olvera-Vargas, H.; Fernández González, Q.; Guillén-Garcés, R.A.; Rincón, M.E. Reverse-Engineered Electro-Fenton for the Selective Synthesis of Oxalic or Oxamic Acid through the Degradation of Acetaminophen: A Novel Green Electrocatalytic Refinery Approach. *Water Res.* **2025**, *272*, 122914. [CrossRef]
18. Ghanbari, F.; Yaghoot-Nezhad, A.; Wacławek, S.; Lin, K.-Y.A.; Rodríguez-Chueca, J.; Mehdipour, F. Comparative Investigation of Acetaminophen Degradation in Aqueous Solution by UV/Chlorine and UV/H_2O_2 Processes: Kinetics and Toxicity Assessment, Process Feasibility and Products Identification. *Chemosphere* **2021**, *285*, 131455. [CrossRef]
19. Serna-Galvis, E.A.; Silva-Agredo, J.; Lee, J.; Echavarría-Isaza, A.; Torres-Palma, R.A. Possibilities and Limitations of the Sono-Fenton Process Using Mid-High-Frequency Ultrasound for the Degradation of Organic Pollutants. *Molecules* **2023**, *28*, 1113. [CrossRef]
20. Camargo-Perea, A.L.; Serna-Galvis, E.A.; Lee, J.; Torres-Palma, R.A. Understanding the Effects of Mineral Water Matrix on Degradation of Several Pharmaceuticals by Ultrasound: Influence of Chemical Structure and Concentration of the Pollutants. *Ultrason. Sonochem.* **2021**, *73*, 105500. [CrossRef] [PubMed]
21. Trujillano, R.; Rives, V.; García, I. Photocatalytic Degradation of Paracetamol in Aqueous Medium Using TiO_2 Prepared by the Sol–Gel Method. *Molecules* **2022**, *27*, 2904. [CrossRef] [PubMed]
22. Wang, L.; Bian, Z. Photocatalytic Degradation of Paracetamol on Pd–$BiVO_4$ under Visible Light Irradiation. *Chemosphere* **2020**, *239*, 124815. [CrossRef]
23. Guettaıa, D.; Gaffour, H. Photo-Catalytıc Degradatıon of Paracetamol Using a Novel Photocatalyst Zr–WO_3 Doped Charcoal. *React. Kinet. Mech. Catal.* **2025**, *138*, 533–550. [CrossRef]
24. Muga, H.E.; Mihelcic, J.R. Sustainability of Wastewater Treatment Technologies. *J. Environ. Manag.* **2008**, *88*, 437–447. [CrossRef]
25. Zou, M.; Wei, J.; Qian, Y.; Xu, Y.; Fang, Z.; Yang, X.; Wang, Z. Life Cycle Assessment of Homogeneous Fenton Process as Pretreatment for Refractory Pharmaceutical Wastewater. *Front. Chem. Sci. Eng.* **2024**, *18*, 49. [CrossRef]
26. Hurtado, L.; Romero, R.; Mendoza, A.; Brewer, S.; Donkor, K.; Gómez-Espinosa, R.M.; Natividad, R. Paracetamol Mineralization by Photo Fenton Process Catalyzed by a Cu/Fe-PILC under Circumneutral PH Conditions. *J. Photochem. Photobiol. A Chem.* **2019**, *373*, 162–170. [CrossRef]
27. Abdelhaleem, A.; Abdelhamid, H.N.; Ibrahim, M.G.; Chu, W. Photocatalytic Degradation of Paracetamol Using Photo-Fenton-like Metal-Organic Framework-Derived CuO@C under Visible LED. *J. Clean. Prod.* **2022**, *379*, 134571. [CrossRef]
28. Hernández-Oloño, J.T.; Vargas-Hernández, D.; Castro-Campoy, D.A.; Ibarra-Espinoza, A.; Pérez-Cruz, M.A.; Garrafa-Gálvez, H.E.; Herrera-Urbina, J.R.; Tánori-Córdova, J.C. Photo-Catalytic Activity of Iron Nanoparticles Supported on SBA-15 for Degradation of Organic Pollutants. *J. Photochem. Photobiol. A Chem.* **2025**, *469*, 116597. [CrossRef]
29. Grifasi, N.; Deorsola, F.A.; Fino, D.; Piumetti, M. Mesoporous TiO_2 and Fe-Containing TiO_2 Prepared by Solution Combustion Synthesis as Catalysts for the Photodegradation of Paracetamol. *Environ. Sci. Pollut. Res.* **2024**, *31*, 36861–36881. [CrossRef] [PubMed]
30. Jin, C.; Han, B.; Luo, C.; Qin, J.; Liu, Y.; Dai, Z.; Sun, Y.; Gan, Z.; Wang, C.-C.; Zheng, X.; et al. Precise Synthesis of Fe Single-Atom Catalysts on Montmorillonite/g-C_3N_4 Heterostructures for Highly Efficient Fenton-like Degradation of Organic Pollutants. *Water Res.* **2025**, *287*, 124420. [CrossRef]
31. Cheshme Khavar, A.H.; Rashidi, M.A.; Alvandi, M.; Darvishnejad, M.H.; Aghayani, E. Bimetallic CuBi Nanoparticles Modified Ti_3C_2 MXene as an Efficient Cocatalyst for Enhancing Photocatalytic Degradation of Acetaminophen. *Environ. Res.* **2025**, *282*, 122118. [CrossRef]
32. Abid, M.; Howayek, T.M.; Mazur, O.; Viter, R.; Bekheet, M.F.; Nada, A.A.; Bezzerga, D.; Hong, J.; Miele, P.; Iatsunskyi, I.; et al. Innovative Electrospinning Approach to Fabricate TiO_2/NiO Nanofibers for Effective Acetaminophen Degradation. *Colloids Surf. A Physicochem. Eng. Asp.* **2025**, *709*, 136077. [CrossRef]
33. Hachemaoui, M.; Molina, C.B.; Belver, C.; Bedia, J.; Mokhtar, A.; Hamacha, R.; Boukoussa, B. Metal-Loaded Mesoporous MCM-41 for the Catalytic Wet Peroxide Oxidation (CWPO) of Acetaminophen. *Catalysts* **2021**, *11*, 219. [CrossRef]
34. Roman, F.F.; Silva, A.S.; Diaz de Tuesta, J.L.; Baldo, A.P.; Lopes, J.P.M.; Gonçalves, G.; Pereira, A.I.; Praça, P.; Silva, A.M.T.; Faria, J.L.; et al. Plastic Waste-Derived Carbon Nanotubes: Influence of Growth Catalyst and Catalytic Activity in CWPO. *J. Environ. Chem. Eng.* **2025**, *13*, 115206. [CrossRef]
35. Kanakaraju, D.; Glass, B.D.; Goh, P.S. Advanced Oxidation Process-Mediated Removal of Pharmaceuticals from Water: A Review of Recent Advances. *Environ. Sci. Pollut. Res.* **2025**, *32*, 14316–14350. [CrossRef] [PubMed]

36. Oller, I.; Malato, S. Photo-Fenton Applied to the Removal of Pharmaceutical and Other Pollutants of Emerging Concern. *Curr. Opin. Green. Sustain. Chem.* **2021**, *29*, 100458. [CrossRef]
37. Giménez, B.N.; Conte, L.O.; Alfano, O.M.; Schenone, A.V. Paracetamol Removal by Photo-Fenton Processes at near-Neutral PH Using a Solar Simulator: Optimization by D-Optimal Experimental Design and Toxicity Evaluation. *J. Photochem. Photobiol. A Chem.* **2020**, *397*, 112584. [CrossRef]
38. Wypart-Pawul, A.; Neczaj, E.; Grobelak, A. Advanced Oxidation Processes for Removal of Organic Micropollutants from Wastewater. *Desalination Water Treat.* **2023**, *305*, 114–128. [CrossRef]
39. Feijoo, S.; González-Rodríguez, J.; Fernández, L.; Vázquez-Vázquez, C.; Feijoo, G.; Moreira, M.T. Fenton and Photo-Fenton Nanocatalysts Revisited from the Perspective of Life Cycle Assessment. *Catalysts* **2019**, *10*, 23. [CrossRef]
40. Ustun Odabasi, S.; Buyukgungor, H. Comparative Study of Degradation of Pharmaceutical and Personal Care Products in Wastewater by Advanced Oxidation Processes: Fenton, UV/H_2O_2, UV/TiO_2. *Clean* **2024**, *52*, 2300204. [CrossRef]
41. Rodríguez, R.; Espada, J.J.; Pariente, M.I.; Melero, J.A.; Martínez, F.; Molina, R. Comparative Life Cycle Assessment (LCA) Study of Heterogeneous and Homogenous Fenton Processes for the Treatment of Pharmaceutical Wastewater. *J. Clean. Prod.* **2016**, *124*, 21–29. [CrossRef]
42. Serra, A.; Domènech, X.; Brillas, E.; Peral, J. Life Cycle Assessment of Solar Photo-Fenton and Solar Photoelectro-Fenton Processes Used for the Degradation of Aqueous α-Methylphenylglycine. *J. Environ. Monit.* **2011**, *13*, 167–174. [CrossRef]
43. Ribeiro, J.P.; Sarinho, L.; Nunes, M.I. Application of Life Cycle Assessment to Fenton Processes in Wastewater Treatment—A Review. *J. Water Process Eng.* **2024**, *57*, 104692. [CrossRef]
44. Espíndola, J.C.; Cristóvão, R.O.; Mayer, D.A.; Boaventura, R.A.R.; Dias, M.M.; Lopes, J.C.B.; Vilar, V.J.P. Overcoming Limitations in Photochemical UVC/H_2O_2 Systems Using a Mili-Photoreactor (NETmix): Oxytetracycline Oxidation. *Sci. Total Environ.* **2019**, *660*, 982–992. [CrossRef] [PubMed]
45. Thomas, N.; Dionysiou, D.D.; Pillai, S.C. Heterogeneous Fenton Catalysts: A Review of Recent Advances. *J. Hazard. Mater.* **2021**, *404*, 124082. [CrossRef] [PubMed]
46. *ISO 14040:2006*; Environmental Management—Life Cycle assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
47. Valverde, J.L.; Romero, A.; Romero, R.; García, P.B.; Sánchez, M.L.; Asencio, I. Preparation and Characterization of Fe-PILCs. Influence of the Synthesis Parameters. *Clays Clay Min.* **2005**, *53*, 613–621. [CrossRef]
48. Pálinkó, I.; Lázár, K.; Hannus, I.; Kirisci, I. Step towards Nanoscale Fe Moieties: Intercalation of Simple and Keggin-Type Iron-Containing Ions in-between the Layers of Na-Montmorillonite. *J. Phys. Chem. Solids* **1996**, *57*, 1067–1072. [CrossRef]
49. Hurtado, L.; Avilés, O.; Brewer, S.; Donkor, K.K.; Romero, R.; Gómez-Espinosa, R.M.; Alvarado, O.; Natividad, R. Al/Cu-PILC as a Photo-Fenton Catalyst: Paracetamol Mineralization. *ACS Omega* **2022**, *7*, 23821–23832. [CrossRef]
50. PRé Sustainability SimaPro 2025. Available online: https://pre-sustainability.com/ (accessed on 20 June 2025).
51. ecoinvent Ecoinvent v3.10—Ecoinvent. Available online: https://ecoinvent.org/ecoinvent-v3-10/ (accessed on 26 July 2025).
52. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
53. Rosenbaum, R.K.; Bachmann, T.M.; Gold, L.S.; Huijbregts, M.A.J.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H.F.; MacLeod, M.; Margni, M.; et al. USEtox—The UNEP-SETAC Toxicity Model: Recommended Characterisation Factors for Human Toxicity and Freshwater Ecotoxicity in Life Cycle Impact Assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 532–546. [CrossRef]
54. Chatzisymeon, E.; Foteinis, S.; Mantzavinos, D.; Tsoutsos, T. Life Cycle Assessment of Advanced Oxidation Processes for Olive Mill Wastewater Treatment. *J. Clean. Prod.* **2013**, *54*, 229–234. [CrossRef]
55. Huijbregts, M.A.J.; Rombouts, L.J.A.; Ragas, A.M.; van de Meent, D. Human-Toxicological Effect and Damage Factors of Carcinogenic and Noncarcinogenic Chemicals for Life Cycle Impact Assessment. *Integr. Environ. Assess. Manag.* **2005**, *1*, 181–244. [CrossRef]
56. Fantke, P.; Chiu, W.A.; Aylward, L.; Judson, R.; Huang, L.; Jang, S.; Gouin, T.; Rhomberg, L.; Aurisano, N.; McKone, T.; et al. Exposure and Toxicity Characterization of Chemical Emissions and Chemicals in Products: Global Recommendations and Implementation in USEtox. *Int. J. Life Cycle Assess.* **2021**, *26*, 899–915. [CrossRef]
57. Fernandes, S.; Esteves da Silva, J.C.G.; Pinto da Silva, L. Life Cycle Assessment-Based Comparative Study between High-Yield and "Standard" Bottom-Up Procedures for the Fabrication of Carbon Dots. *Materials* **2022**, *15*, 3446. [CrossRef]
58. Fernández, C.; González-Doncel, M.; Pro, J.; Carbonell, G.; Tarazona, J.V. Occurrence of Pharmaceutically Active Compounds in Surface Waters of the Henares-Jarama-Tajo River System (Madrid, Spain) and a Potential Risk Characterization. *Sci. Total Environ.* **2010**, *408*, 543–551. [CrossRef]
59. Zhang, Y.; Guo, S.; Gong, Y.; Wang, L. Potential Trade-off between Water Consumption and Water Quality: Life Cycle Assessment of Nonaqueous Solvent Dyeing. *Water Res.* **2022**, *215*, 118222. [CrossRef]

60. Daniel, D.; Nunes, B.; Pinto, E.; Ferreira, I.M.P.L.V.O.; Correia, A.T. Assessment of Paracetamol Toxic Effects under Varying Seawater PH Conditions on the Marine Polychaete Hediste Diversicolor Using Biochemical Endpoints. *Biology* **2022**, *11*, 581. [CrossRef] [PubMed]
61. Al-Mawali, K.S.; Osman, A.I.; Al-Muhtaseb, A.H.; Mehta, N.; Jamil, F.; Mjalli, F.; Vakili-Nezhaad, G.R.; Rooney, D.W. Life Cycle Assessment of Biodiesel Production Utilising Waste Date Seed Oil and a Novel Magnetic Catalyst: A Circular Bioeconomy Approach. *Renew. Energy* **2021**, *170*, 832–846. [CrossRef]
62. Costamagna, M.; Gonçalves, N.P.F.; Bianco Prevot, A. Environmental Assessment of Humic Acid Coated Magnetic Materials Used as Catalyst in Photo-Fenton Processes. *Catalysts* **2020**, *10*, 771. [CrossRef]
63. Amin, M.; Shah, H.H.; Naveed, A.B.; Iqbal, A.; Gamil, Y.; Najeh, T. Life Cycle Assessment of Iron-Biomass Supported Catalyst for Fischer Tropsch Synthesis. *Front. Chem.* **2024**, *12*, 1374739. [CrossRef]
64. Alanis, C.; Romero, R.; Ávila Córdoba, L.; Natividad, R. Methyl Esters Production from Waste Cooking Oil Catalysed by Iron Oxides Supported on CaO: Cost and Environmental Impacts. *Clean. Circ. Bioecon.* **2024**, *9*, 100109. [CrossRef]
65. Rahman, A.; Kang, S.; McGinnis, S.; Vikesland, P.J. Life Cycle Impact Assessment of Iron Oxide (Fe_3O_4/γ-Fe_2O_3) Nanoparticle Synthesis Routes. *ACS Sustain. Chem. Eng.* **2022**, *10*, 3155–3165. [CrossRef]
66. Negrini, B.; Floris, P.; D'Abramo, C.; Aldaghi, S.A.; Costamagna, M.; Perucca, M.; Saibene, M.; Perelshtein, I.; Colombo, A.; Bonfanti, P.; et al. Comparative Toxicity and Environmental Impact Assessments of Sonochemically-Synthesized CuO and Zn-Doped CuO Nanoparticles Using Zebrafish and LCA Tools. *Discov. Nano* **2025**, *20*, 51. [CrossRef]
67. Marimón-Bolívar, W.; González, E.E. Green Synthesis with Enhanced Magnetization and Life Cycle Assessment of Fe_3O_4 Nanoparticles. *Environ. Nanotechnol. Monit. Manag.* **2018**, *9*, 58–66. [CrossRef]
68. Patiño-Ruiz, D.A.; Meramo-Hurtado, S.I.; González-Delgado, Á.D.; Herrera, A. Environmental Sustainability Evaluation of Iron Oxide Nanoparticles Synthesized via Green Synthesis and the Coprecipitation Method: A Comparative Life Cycle Assessment Study. *ACS Omega* **2021**, *6*, 12410–12423. [CrossRef]
69. Borthakur, P.P.; Borthakur, B. The Role of Industrial Catalysts in Accelerating the Renewable Energy Transition. *Chem. Proc.* **2025**, *17*, 6. [CrossRef]
70. Karan, P.; Chakraborty, R. E-Waste Derived Silica-Alumina for Eco-Friendly and Inexpensive Mg-Al-Ti Photocatalyst towards Glycerol Carbonate (Electrolyte) Synthesis: Process Optimization and LCA. *Waste Manag.* **2022**, *140*, 213–224. [CrossRef] [PubMed]
71. Jambhule, P.W.; Khaty, N.T.; Das Sarma, I.B.; Tangde, V.M.; Joglekar, S.; Wankhede, G.A. Towards Green Synthesis of Magnetite Nanoparticles: A Comparative Life Cycle Assessment (LCA) of Deep Eutectic Solvent-Based Synthesis of Magnetite Nanoparticles and Conventional Methods. *Inorg. Chem. Commun.* **2025**, *179*, 114721. [CrossRef]
72. Ferdous, S.; Gracida-Alvarez, U.R.; Ferrandon, M.; Delferro, M.; Benavides, P.T.; Urgun-Demirtas, M. Techno-Economic and Life Cycle Analyses of the Synthesis of a Platinum–Strontium Titanate Catalyst. *Catal. Sci. Technol.* **2025**, *15*, 4419–4429. [CrossRef]
73. United Nations Economic Commission For Europe. *Life Cycle Assessment of Electricity Generation Options*; United Nations Economic Commission For Europe: Geneva, Switzerland, 2022.
74. Yoshida, H.; Yun, Y.; Hsu, Y. Catalysis Towards Sustainability. *Adv. Energy Sustain. Res.* **2025**, *6*, 1–4. [CrossRef]
75. Zepon Tarpani, R.R.; Azapagic, A. Life Cycle Environmental Impacts of Advanced Wastewater Treatment Techniques for Removal of Pharmaceuticals and Personal Care Products (PPCPs). *J. Environ. Manag.* **2018**, *215*, 258–272. [CrossRef]
76. Nyberg, O.; Rico, A.; Guinée, J.B.; Henriksson, P.J.G. Characterizing Antibiotics in LCA—A Review of Current Practices and Proposed Novel Approaches for Including Resistance. *Int. J. Life Cycle Assess.* **2021**, *26*, 1816–1831. [CrossRef]
77. Morais, S.A.; Delerue-Matos, C.; Gabarrell, X. Accounting for the Dissociating Properties of Organic Chemicals in LCIA: An Uncertainty Analysis Applied to Micropollutants in the Assessment of Freshwater Ecotoxicity. *J. Hazard. Mater.* **2013**, *248–249*, 461–468. [CrossRef]
78. Mishra, R.K.; Mentha, S.S.; Misra, Y.; Dwivedi, N. Emerging Pollutants of Severe Environmental Concern in Water and Wastewater: A Comprehensive Review on Current Developments and Future Research. *Water-Energy Nexus* **2023**, *6*, 74–95. [CrossRef]
79. Tian, L.; Mi, N.; Wang, L.; Huang, C.; Fu, W.; Bai, M.; Gao, L.; Ma, H.; Zhang, C.; Lu, Y.; et al. Regular Use of Paracetamol and Risk of Liver Cancer: A Prospective Cohort Study. *BMC Cancer* **2024**, *24*, 33. [CrossRef]
80. Sirois, J.E. Comprehensive Investigation Evaluating the Carcinogenic Hazard Potential of Acetaminophen. *Regul. Toxicol. Pharmacol.* **2021**, *123*, 104944. [CrossRef] [PubMed]
81. Jaeschke, H.; Murray, F.J.; Monnot, A.D.; Jacobson-Kram, D.; Cohen, S.M.; Hardisty, J.F.; Atillasoy, E.; Hermanowski-Vosatka, A.; Kuffner, E.; Wikoff, D.; et al. Assessment of the Biochemical Pathways for Acetaminophen Toxicity: Implications for Its Carcinogenic Hazard Potential. *Regul. Toxicol. Pharmacol.* **2021**, *120*, 104859. [CrossRef]
82. Pesqueira, J.F.J.R.; Pereira, M.F.R.; Silva, A.M.T. A Life Cycle Assessment of Solar-Based Treatments (H_2O_2, TiO_2 Photocatalysis, Circumneutral Photo-Fenton) for the Removal of Organic Micropollutants. *Sci. Total Environ.* **2021**, *761*, 143258. [CrossRef]
83. Foteinis, S.; Monteagudo, J.M.; Durán, A.; Chatzisymeon, E. Environmental Sustainability of the Solar Photo-Fenton Process for Wastewater Treatment and Pharmaceuticals Mineralization at Semi-Industrial Scale. *Sci. Total Environ.* **2018**, *612*, 605–612. [CrossRef] [PubMed]

84. Ecetoc. *Freshwater Ecotoxicity as an Impact Category in Life Cycle Assessment*; Technical Report No. 127; Ecetoc: Brussels, Belgium, 2016; p. 106.
85. Katal, R.; Davood Abadi Farahani, M.H.; Jiangyong, H. Degradation of Acetaminophen in a Photocatalytic (Batch and Continuous System) and Photoelectrocatalytic Process by Application of Faceted-TiO_2. *Sep. Purif. Technol.* **2020**, *230*, 115859. [CrossRef]
86. Nunes, B.; Antunes, S.C.; Santos, J.; Martins, L.; Castro, B.B. Toxic Potential of Paracetamol to Freshwater Organisms: A Headache to Environmental Regulators? *Ecotoxicol. Env. Saf.* **2014**, *107*, 178–185. [CrossRef]
87. Kock, A.; Glanville, H.C.; Law, A.C.; Stanton, T.; Carter, L.J.; Taylor, J.C. Emerging Challenges of the Impacts of Pharmaceuticals on Aquatic Ecosystems: A Diatom Perspective. *Sci. Total Environ.* **2023**, *878*, 162939. [CrossRef]
88. Samanta, C. Direct Synthesis of Hydrogen Peroxide from Hydrogen and Oxygen: An Overview of Recent Developments in the Process. *Appl. Catal. A Gen.* **2008**, *350*, 133–149. [CrossRef]
89. Całus-Makowska, K.; Dziubińska, J.; Grosser, A.; Grobelak, A. Application of the Fenton and Photo-Fenton Processes in Pharmaceutical Removal: New Perspectives in Environmental Protection. *Desalination Water Treat.* **2025**, *321*, 100949. [CrossRef]
90. Novoa-Luna, K.A.; Mendoza-Zepeda, A.; Natividad, R.; Romero, R.; Galar-Martínez, M.; Gómez-Oliván, L.M. Biological Hazard Evaluation of a Pharmaceutical Effluent before and after a Photo-Fenton Treatment. *Sci. Total Environ.* **2016**, *569–570*, 830–840. [CrossRef]
91. Grisales, C.M.; Salazar, L.M.; Garcia, D.P. Treatment of Synthetic Dye Baths by Fenton Processes: Evaluation of Their Environmental Footprint through Life Cycle Assessment. *Environ. Sci. Pollut. Res.* **2019**, *26*, 4300–4311. [CrossRef]
92. Li, Y.; Zhang, S.; Zhang, W.; Xiong, W.; Ye, Q.; Hou, X.; Wang, C.; Wang, P. Life Cycle Assessment of Advanced Wastewater Treatment Processes: Involving 126 Pharmaceuticals and Personal Care Products in Life Cycle Inventory. *J. Environ. Manag.* **2019**, *238*, 442–450. [CrossRef]
93. Surra, E.; Correia, M.; Figueiredo, S.; Silva, J.G.; Vieira, J.; Jorge, S.; Pazos, M.; Sanromán, M.Á.; Lapa, N.; Delerue-Matos, C. Life Cycle and Economic Analyses of the Removal of Pesticides and Pharmaceuticals from Municipal Wastewater by Anodic Oxidation. *Sustainability* **2021**, *13*, 3669. [CrossRef]
94. Cornejo-Cornejo, L.G.; Romero, R.; Gutiérrez-Alejandre, A.; Regalado-Méndez, A.; Amado-Piña, D.; Hernández-Servín, J.A.; Natividad, R. Iron and Copper Pillared Clay Photo-Catalyzes Carbon Dioxide Chemical Reduction in Aqueous Medium. *Chem. Eng. J.* **2025**, *511*, 162193. [CrossRef]
95. Natividad, R. Wastewater Upgrading to Fuels: Routes and Challenges. *J. Chem. Eng. Renew. Fuels* **2025**, *1*, 3–8. [CrossRef]
96. Muñoz, I.; Rieradevall, J.; Torrades, F.; Peral, J.; Domènech, X. Environmental Assessment of Different Advanced Oxidation Processes Applied to a Bleaching Kraft Mill Effluent. *Chemosphere* **2006**, *62*, 9–16. [CrossRef]
97. Arzate, S.; Pfister, S.; Oberschelp, C.; Sánchez-Pérez, J.A. Environmental Impacts of an Advanced Oxidation Process as Tertiary Treatment in a Wastewater Treatment Plant. *Sci. Total Environ.* **2019**, *694*, 133572. [CrossRef] [PubMed]
98. Garciamontano, J.; Ruiz, N.; Munoz, I.; Domenech, X.; Garciahortal, J.; Torrades, F.; Peral, J. Environmental Assessment of Different Photo-Fenton Approaches for Commercial Reactive Dye Removal. *J. Hazard. Mater.* **2006**, *138*, 218–225. [CrossRef]
99. Ioannou-Ttofa, L.; Foteinis, S.; Chatzisymeon, E.; Michael-Kordatou, I.; Fatta-Kassinos, D. Life Cycle Assessment of Solar-driven Oxidation as a Polishing Step of Secondary-treated Urban Effluents. *J. Chem. Technol. Biotechnol.* **2017**, *92*, 1315–1327. [CrossRef]
100. Foteinis, S.; Borthwick, A.G.L.; Frontistis, Z.; Mantzavinos, D.; Chatzisymeon, E. Environmental Sustainability of Light-Driven Processes for Wastewater Treatment Applications. *J. Clean. Prod.* **2018**, *182*, 8–15. [CrossRef]