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Comparative life cycle assessment in wastewater treatment plants: scenario analysis with OpenLCA

Avaliação comparativa de ciclo de vida em estações de tratamento de esgoto: análise de cenários com OpenLCA

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ABSTRACT

Although they play a crucial environmental role, wastewater treatment plants (WWTPs) also generate environmental impacts due to resource consumption and waste production. Therefore, the application of the life cycle assessment (LCA) methodology is of fundamental importance for a comprehensive analysis of the impacts associated with these systems. This work aims to perform an LCA of a tertiary-level WWTP, consisting of an anaerobic reactor followed by activated sludge, in order to select the most sustainable scenario. Open Source Life Cycle Assessment (OpenLCA) was the software used, along with the Ecoinvent, BIOENERGIEDAT_18, ELCD, and NEEDS databases. The reference methods for calculating impact categories were CML-IA and ReCiPe. Three scenarios were simulated: CT_Base, CT_Solar, and CT_Reuse. All models considered the operation and maintenance (O&M) phase. The CT_Base scenario assumed the WWTP operates as it currently does (electricity from hydropower), the CT_Solar scenario operated entirely on solar energy, and the CT_Reuse scenario established the reusing of 25% of the treated effluent. The functional unit (FU) adopted corresponded to the volume of wastewater treated over 15 years of O&M of the WWTP. For both methods applied, the CT_Solar scenario was the most environmentally advantageous. The amount of gases emitted in the CT_Reuse scenario during the transportation of treated effluent to reuse points increased negative impacts and consequently environmental degradation across various categories, making it the least sustainable scenario.

Keywords: sustainability; OpenLCA; environmental viability; environmental impact.

RESUMO

Apesar de desempenharem papel ambiental crucial, as estação de tratamento de efluente (ETE) também geram impactos ambientais em razão da demanda por recursos e da geração de resíduos. Dessa forma, de fundamental importância é a aplicação da metodologia de Avaliação de Ciclo de Vida (ACV) para uma análise global dos impactos provenientes delas. Este trabalho objetivou realizar a ACV de uma ETE de nível terciária, composta de reator anaeróbio seguido de lodos ativados, visando selecionar o cenário mais sustentável. O OpenLCA foi o *software* utilizado, junto com as bases de dados Ecoinvent, BIOENERGIEDAT_18, ELCD e NEEDS. Os métodos de referência para os cálculos das categorias de impacto foram CML-IA e ReCiPe. Três cenários foram simulados, o *CT_Base*, *CT_Solar* e o *CT_Reúso*. Todos foram modelados considerando a fase de operação e manutenção (O&M). O *CT_Base* admitiu a ETE conforme opera atualmente (energia elétrica por geração hidráulica), o *CT_Solar* opera totalmente por meio de energia solar e o *CT_Reúso* estabeleceu o reúso de 25% do efluente tratado. A unidade funcional (UF) adotada correspondeu ao volume de esgoto tratado em 15 anos de O&M da ETE. Para ambos os métodos aplicados, o *CT_Solar* se mostrou o cenário mais vantajoso ambientalmente. A quantidade de gases emitida no *CT_Reúso*, quando do transporte do efluente tratado para os pontos de reúso, potencializou os impactos negativos e consequentemente a degradação ambiental em diversas categorias, tornando-o assim o cenário menos sustentável.

Palavras-chave: sustentabilidade; OpenLCA; viabilidade ambiental; impactos ambientais.

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Introduction

Wastewater treatment plants (WWTPs) play a fundamental role in the development of social well-being and environmental harmony. In these facilities, sewage is properly treated and discharged into water bodies in accordance with current legislation, or reused, thereby mitigating the negative impacts caused by untreated sewage (Dufner et al., 2022; Kar et al., 2023; Pasciucco et al., 2023; Rashid et al., 2023).

However, despite playing a significant environmental role, WWTPs also cause negative environmental impacts, as during their treatment processes, throughout the phases that comprehend their life cycle––construction, operation and maintenance (O&M) and end of life––they consume raw materials and energy and generate various wastes, such as gaseous emissions (odors, biogas, etc.) and solid residues (sludge, sand, etc.) (Tian et al., 2020; Al-Anbari et al., 2022). According to Kar et al. (2023) and Pasciucco et al. (2023), the three phases that make up the life cycle of WWTPs impact the environment in different ways.

Life cycle assessment (LCA) methodology is one of the tools that allows for the analysis of impacts throughout an entire supply chain of a product, process, or service (Sudarno et al., 2024). According to Parra-Saldivar et al. (2020), Daskiran et al. (2022), and Sheikholeslami et al. (2022), its application is already widely established worldwide across various industrial sectors, and over the past three decades, it has been increasingly recognized for its applicability in the sanitation sector, specifically in WWTPs (Talang et al., 2022; Rashid et al., 2023).

Basically, the application of the LCA methodology aims to categorize and measure environmental impacts from the raw material extraction phase at the source, passing through its various transformation, usage, and disposal processes, in addition to the transportation inherent to each of these stages.

Accordingly, as noted by Alizadeh et al. (2020), Daskiran et al. (2022), Rashid et al. (2023), and Mancini et al. (2024), applying the LCA methodology to WWTPs allows impacts to be measured, for example, from the production of chemical reagents required for treatment processes (depending on the type of WWTP), as well as from the energy consumption (regardless of the energy matrix), up to the final processes (biogas production, transportation of solid waste to landfills, etc.). Thus, a systemic assessment of impacts throughout the entire life cycle is possible, rather than focusing solely on environmental parameters related to the final discharge into water bodies.

The vast majority of studies on the LCA methodology in WWTPs are based on the variation of treatment scenarios (either altering the treatment type or varying subprocesses within the same type, such as discharging into water bodies or reusing effluent in agriculture), aiming to identify the least impactful and consequently the most sustainable scenario. In other words, it essentially seeks an optimization of the resources applied through maximum reuse throughout the supply chain (Gallego-Schmid and Tarpani, 2019; Pasciucco et al., 2023; Torre et al., 2024).

Regarding the analyzed phase (construction, operation and maintenance [O&M], and end-of-life), the literature review conducted by Lopes et al. (2017), related to the application of LCA in WWTPs, concludes that the magnitude of impacts generated during the end-of-life phase is insignificant compared to the construction and operation phases. The study also finds that, among the reviewed articles, the O&M phase is the most impactful. There is a convergence in the conclusion of Lopes et al. (2017) and various other works on the topic, such as those of Maktabifard et al. (2020), Yang et al. (2021), Lima et al. (2022), Patel and Singh (2022), and Rufí-Salís et al. (2022).

Brazil is a country that still requires substantial investments in the basic sanitation sector (Leite et al., 2022). In the area of sanitation, the low coverage rate of this service is a concern among specialists, as it directly impacts public health. According to the National Sanitation Information System (SNIS, 2022), only 51.2% of the sewage generated nationwide is treated. This figure falls significantly short of the target set by the revision of the New Sanitation Legal Framework, which aims for 90% coverage by the year 2033 (Brasil, 2020). However, Law No. 14,026/2020 has also established that, in the pursuit of universalization, efficiency––including energy efficiency––and the economic-environmental sustainability of the new systems to be designed and operated should also be considered (Brasil, 2020). According to SNIS (2022), electricity consumption in the sanitation sector accounts for one of the highest operational costs of this service, with a progressive increase over the years. This energy consumption not only causes significant environmental impacts (depending on the energy matrix chosen) but also raises the tariffs charged to the populations served by sanitation companies (Shanmugam et al., 2022; Karolinczak et al., 2024).

Therefore, the need to build multiple WWTPs across the country, with appropriate designs that encompass suitable treatment types for each situation, respecting the principles of efficiency and economic-environmental sustainability, aligns with the application of the LCA methodology. Based on this tool, it is possible to simulate alternative scenarios with the goal of identifying the most environmentally, technically, and economically viable perspective while also minimizing operational costs (Awad et al., 2024).

In Brazil, although the use of the LCA methodology in WWTPs has been gaining recognition in recent years (Araújo et al., 2022; Lima et al., 2022), it still needs to be further explored, both in terms of developing databases that encompass the various regional particularities and in considering the numerous combinations of treatment typologies (Gallego-Schmid and Tarpani, 2019; Lima et al., 2022).

Therefore, based on LCA, sanitation company managers will need to make objective and strategic decisions on how to choose the most advantageous project, selecting the design that maximizes the reduction of environmental impacts and optimizes the use of financial resources without compromising efficiency (Boldrin et al., 2022; Marami et al., 2022; Shanmugam et al., 2022), as stipulated by Law No. 14,026/2020.

Given the aforementioned facts, the objective of this work is to evaluate the magnitude of environmental impacts generated by the processes inherent to the operational routine of a tertiary-level WWTP located in the Northeast region of Brazil, using the LCA methodology during the O&M phase across different scenarios, with the aim of identifying the most sustainable scenario.

Methodology

Location and study period

The study was conducted at a WWTP located in the Northeast region of Brazil, in the state of Rio Grande do Norte, a tropical climate region. The data analyzed refer to a monitoring period of 30 months, collected using validated instruments appropriate to each variable: a large-scale meter (macrometer) for flow measurement and standardized laboratory equipment for physicochemical and biological tests.

Characterization of the study area

The WWTP has two treatment modules operating in parallel, each with a treatment capacity of 225 L/s, both currently in operation. It removes nutrients through nitrification and denitrification, with a final flow rate of 450 L/s. The two modules are preceded by mechanized preliminary treatment units (coarse screening, fine screening, and grit chamber). After preliminary treatment, the sewage flow is divided into two lines, each directed to a separate module. Each module contains four upflow anaerobic sludge blanket (UASB) reactors, an anoxic chamber, an aeration tank, and a secondary decanter. Finally, the flows from the two lines converge into the last treatment stage: an ultraviolet (UV) radiation disinfection unit so that the treated wastewater can be discharged into the recipient body.

Regarding the solid phase, the sludge tank stores and mixes the solid material originating from the UASB reactors and the surfaces of the secondary decanters, then directs it to the dewatering unit via centrifugation. Once dewatered, the sludge, along with sand and coarse solids, is transported to the nearest landfill, approximately 23 km away from the station.

Standardization, software, databases, and impact assessment methods

The analysis was conducted according to the LCA methodology, guided by the Brazilian Technical Standard/International Organization for Standardization (NBR ISO) 14040 (ABNT, 2009a) and NBR ISO 14044 (ABNT, 2009b). According to ABNT (2009a, 2009b), the analysis comprised four phases: goal and scope definition; inventory analysis; impact assessment; and interpretation.

The software used was Open Source Life Cycle Assessment (OpenLCA) version 2.1.1. According to Silva et al. (2019), OpenLCA, along with commercial software such as SimaPro, GaBi, and Umberto, is among the most widely used tools for applying the LCA methodology worldwide. However, the fact that OpenLCA is free enables its large-scale use for academic purposes.

Regarding the databases used, due to the absence of certain products/processes that are part of the system flows in the Ecoinvent database (free version), such as sludge, a combination of four databases was chosen: Ecoinvent version 3.7.1; BIOENERGIEDAT_18 (which includes processes related to energy chains based on German research); European reference Life Cycle Database (ELCD) version 2_18; and New Energy Externalities Developments for Sustainability (NEEDS), which covers energy inventories from various sources such as nuclear, solar, wind, and hydro.

Regarding impact assessment methods, ReCiPe 2016 Midpoint (H) and CML-IA baseline were employed. These methods have extensive applicability in studies that use the LCA methodology in WWTPs, both nationally and internationally.

Goal and scope definition

The objective of this work was to evaluate the environmental performance of a tertiary-level WWTP, consisting of an anaerobic reactor, activated sludge, and a disinfection unit, through the application of the LCA methodology during the O&M phase, across three different scenarios, with the aim of identifying the most sustainable one.

Definition of the functional unit

The volume of sewage (in m^3) treated at the WWTP during the 15-year period was defined as the FU of this study. The selection of this period is related to the lifespan of the WWTP in question (15 years). During this period, the management approaches for the effluents produced at the WWTP, as well as its by-products and generated residues (biogas, sludge, sand, and coarse solids), were considered. The treatment, transportation, and final disposal phases of the effluents and residues were delineated according to the boundary setting.

Boundary and scenario delineation

A boundary was established for each scenario. The system boundaries were delineated from the point where raw sewage arrives at the WWTP to the discharge of the final treated effluent (either into the water body only or into the water body and irrigation jointly, as described in each scenario), considering the entire O&M phase. The construction and end-of-life phases were not included because their impact magnitudes are considered negligible compared to those from the O&M phase. Additionally, the lack of precise information about these phases (such as designs and budgets) made detailed analysis unfeasible. The emissions associated with transporting sludge, sand, and coarse solids to the landfill, located 23 km from the WWTP, were included in all scenarios.

Three scenarios were analyzed. The first, called *CT_Base*, represents the current operation of the WWTP, as described earlier in the characterization of the study area. In this scenario, all the electrical energy consumed by the WWTP is supplied by the local state energy company. All impacts associated with the energy production from hydropower plants, as well as their distribution, are included in this scenario. All the liquid effluent generated will be discharged into the water body.

In scenario 2, called *CT_Solar*, a supply of energy entirely generated from solar power through photovoltaic panels was considered. Therefore, all impacts from the manufacturing of the photovoltaic panels were included. In this scenario, all the liquid effluent will also be discharged into the receiving water body.

In the final scenario, called *CT_Reuse*, all the electrical energy consumed by the WWTP is supplied by the local utility; however, 75% of the liquid effluent's FU will be discharged into the receiving water body, while the remaining portion will be used for irrigation of squares and flowerbeds throughout the city (which does not occur currently), transported via water trucks with an 8 m^3 capacity. In *CT_Reuse*, emissions related to the transportation of the portion of treated effluent used for irrigation were also considered. For this purpose, a transportation distance of 30 km was adopted.

The adoption of the *CT_Solar* and *CT_Reuse* scenarios was based on their representation of two promising sustainability strategies in the sanitation sector, which are still relatively underexplored in LCA studies applied to WWTPs.

The selection of 25% of the treated effluent for reuse in the *CT_Reuse* scenario was based on a realistic estimate of operational feasibility and logistical considerations, taking into account the limitations of transport via water trucks and the potential demand for urban irrigation. This percentage was adopted as a representative value capable of demonstrating the environmental impacts of this practice without compromising the system's functionality or overestimating the treated effluent's distribution capacity.

Figures 1, 2, and 3, respectively, illustrate the boundaries of the *CT_Base*, *CT_Solar*, and *CT_Reuse* scenarios.

Figures 4 and 5, respectively, illustrate the directions of the flows (in their various phases) occurring during the wastewater treatment process at the WWTP in scenarios *CT_Base* and *CT_Reuse*. It is important to highlight that regarding these flows, the *CT_Base* and *CT_Solar* scenarios are identical, differing only in the source of electrical energy (hydropower and solar, respectively).

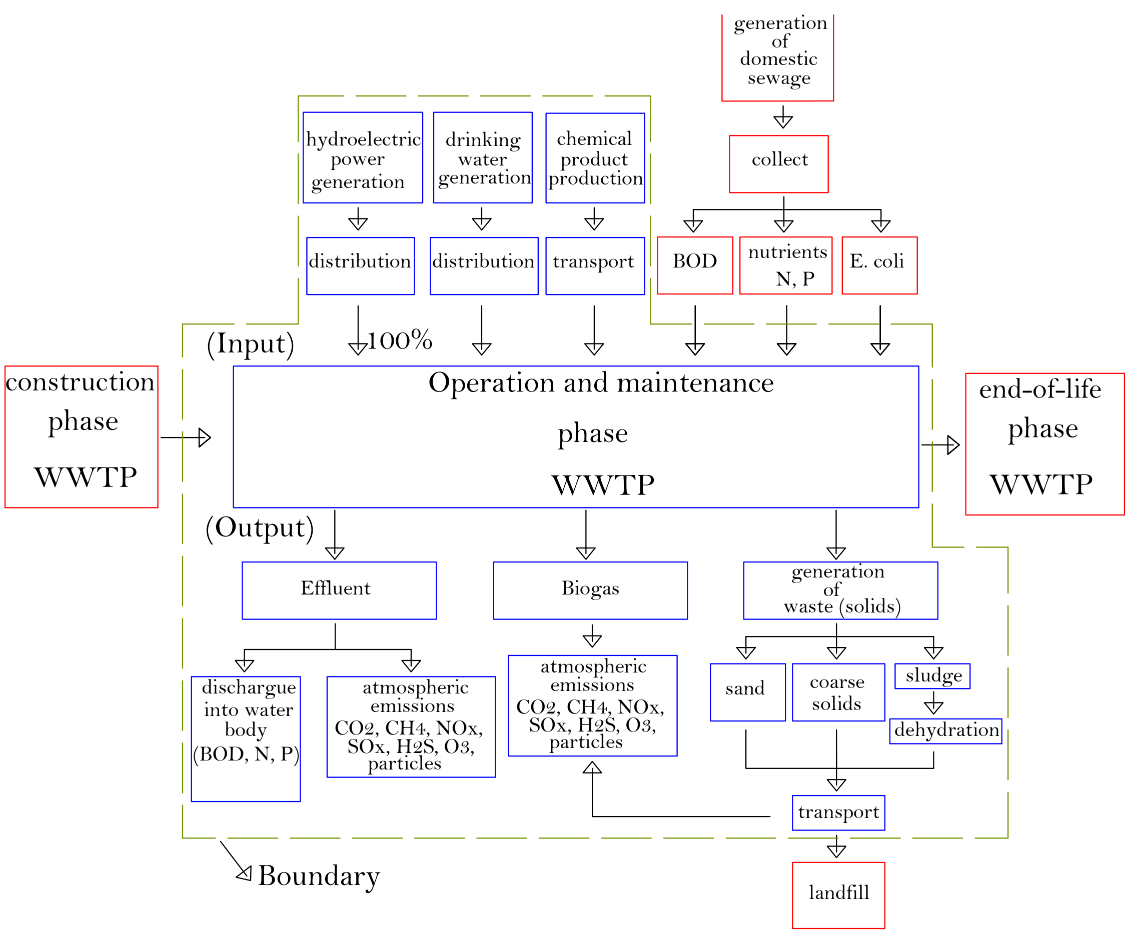

Figure 1 – *CT_Base* scenario – WWTP currently operating.

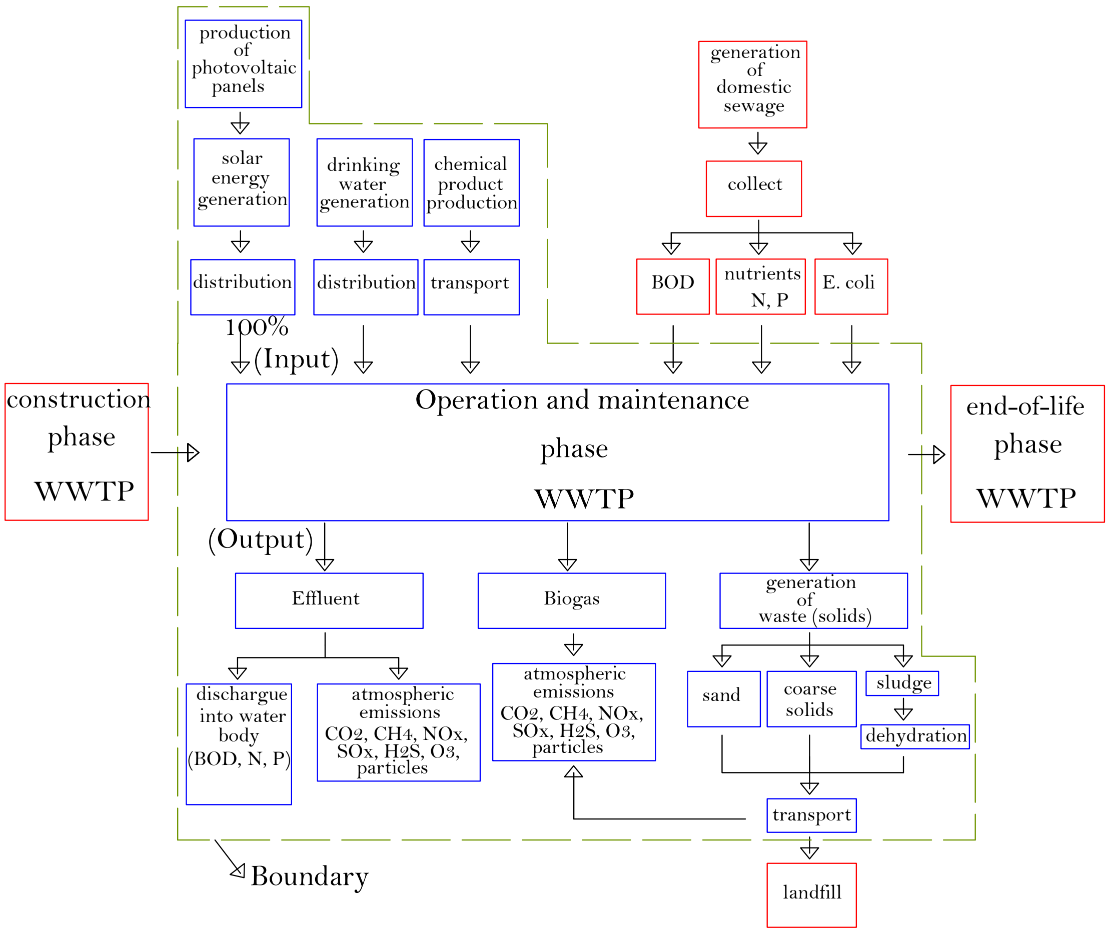

Figure 2 – *CT_Solar* scenario – WWTP 100% operating with solar energy.

Results and discussion

Inventories

Table 1 presents the inventories from the O&M phase of the three modeled scenarios in the OpenLCA software. According to Saavedra-Rubio et al. (2022), of the four stages that make up the LCA methodology (goal and scope definition; inventory analysis; impact assessment; and interpretation), the inventory analysis stage requires the most time and care from researchers. It involves the processes of data collection and the determination of system inputs and outputs, which must be consistent with the selected FU.

The quantities related to air emissions from biogas were based on the methodology proposed by Kalbar et al. (2013). As for emissions associated with the transportation of sludge, dry sand, and coarse solids to the sanitary landfill, data provided by Detran and Feema (2001) and De Carvalho (2011) were used. All other quantities were calculated considering actual data from the WWTP, collected onsite. It is important to highlight that, in the three scenarios, the distance considered from the WWTP to the landfill was 23 km. In the *CT-Reuse* scenario, the average transportation distance for the reuse of 25% of the treated effluent in planters and park gardens was 30 km.

Environmental impacts

Table 2 presents the values of the environmental impacts obtained through the simulations of the *CT_Base*, *CT_Solar*, and *CT_Reuse* scenarios for the categories analyzed using the CML-IA baseline method. For each scenario, the absolute impact values are shown, as well as their relative significance in percentage terms compared to the other scenarios. The units for each impact category are listed in column 1.

Figure 6 shows the comparison among the three scenarios with the normalized impact values (expressed in percentage terms). The internal normalization process of the results is necessary because the reference units for the impact categories are different, making direct comparisons between them impossible. Therefore, to enable these comparisons, each impact category was divided by a common reference value––the maximum value among the alternatives (the scenarios)––resulting in a dimensionless value.

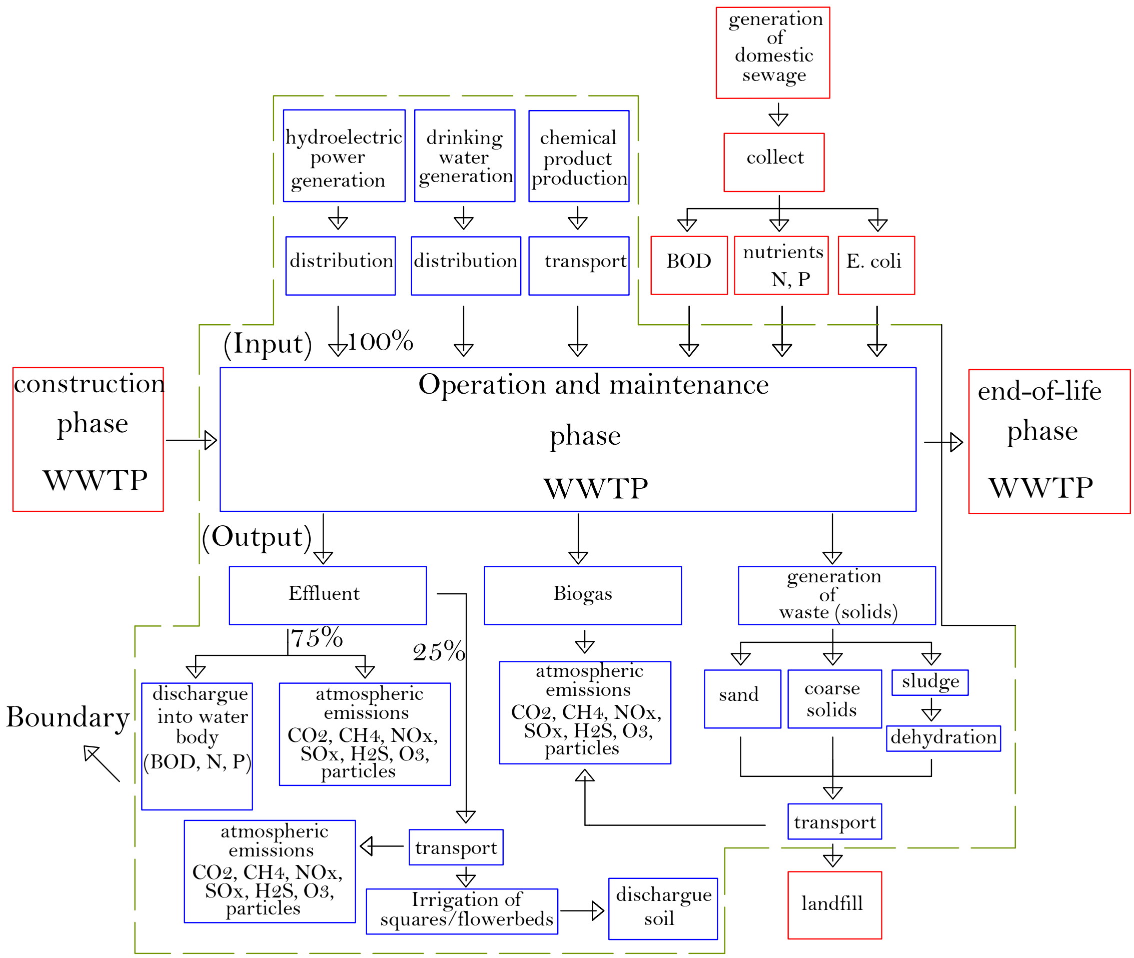

Figure 3 – *CT_Reuse* scenario – WWTP reusing 25% of the effluent flow.

Based on the analysis of Figure 6, it is observed that, regarding the CML-IA baseline method, the *CT_Solar* scenario was the least impactful in nine impact categories (abiotic depletion of fossil fuels, acidification, eutrophication, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation, and terrestrial ecotoxicity). Only in the categories of abiotic depletion and freshwater aquatic ecotoxicity did this scenario show a higher impact compared to the others. The fact that this scenario uses electricity generated from solar energy during the O&M phase significantly contributes to reducing impacts in most categories. These results align with the studies by Awad et al. (2024) and Jamaludin et al. (2024), which analyze WWTPs with activated sludge. Among the impact categories, eutrophication stands out, as a beneficial impact was observed in this category when the *CT_Solar* scenario was simulated.

On the other hand, the *CT_Reuse* scenario was characterized as the most impactful in those nine categories. The fact that *CT_Reuse* considers transportation by tanker trucks of the 25% portion of treated effluent for irrigation of planters and parks results in the emission of greenhouse gases that amplify environmental impacts across several categories, making it the least environmentally advantageous. In no impact category was the *CT_Base* scenario more impactful than the *CT_Reuse*.

Similar to the CML method, the ReCiPe 2016 Midpoint (H) method was also used to determine the environmental impacts for the three scenarios. Table 3 displays the impact values (both absolute and normalized) for this method.

Figure 7 shows the comparison of the normalized impact category values calculated using the ReCiPe method for the three scenarios. Once again, the *CT_Solar* scenario proved to be the least impactful. Out of the 18 impact categories analyzed by this method, the *CT_Solar* was the least impactful in 12 of them. In the marine eutrophication and water consumption categories, this scenario stood out by having a beneficial impact. The *CT_Reuse* scenario consolidates as the most impactful, reaching the highest value among the analyzed scenarios in 11 impact categories.

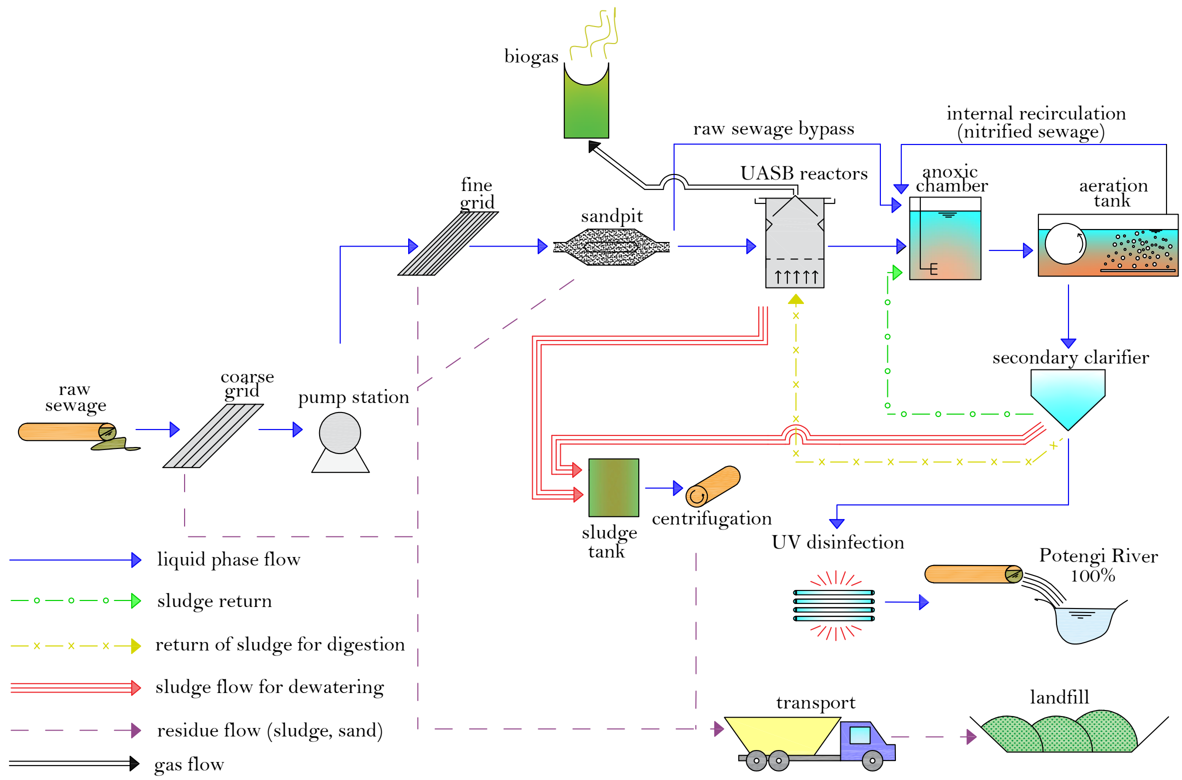

Figure 4 – *CT_Base* scenario flows.

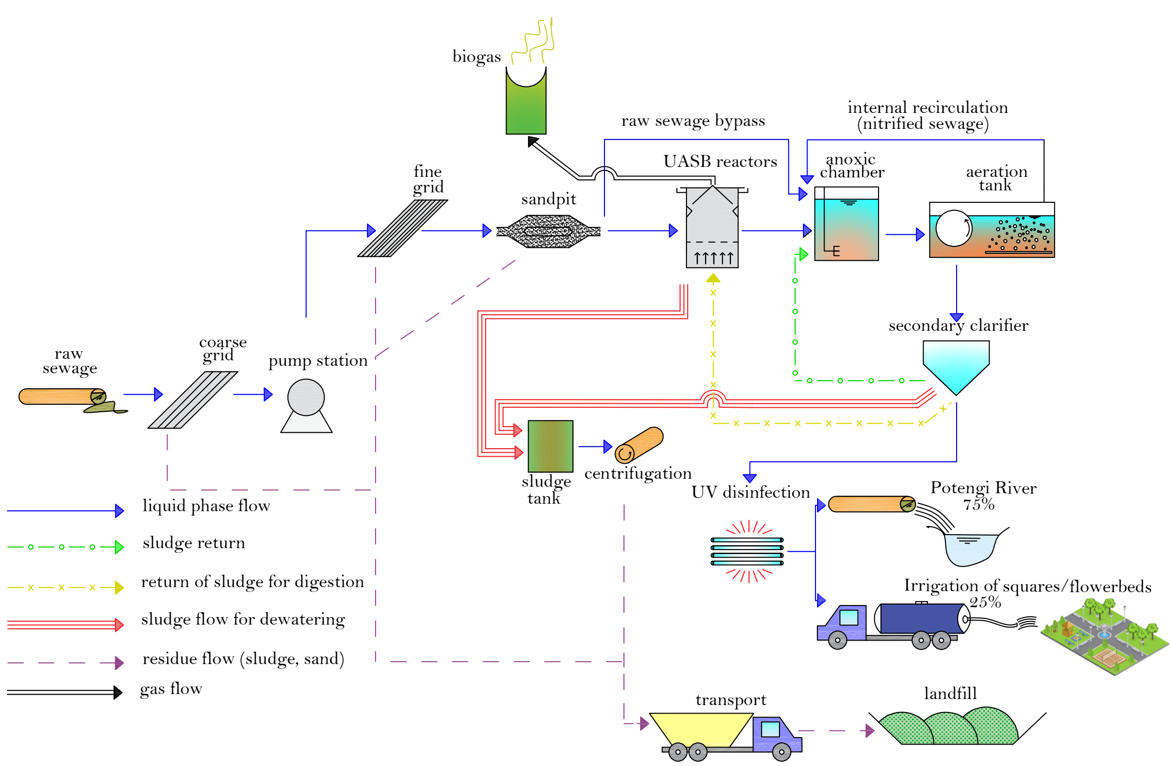

Figure 5 – *CT_Reuse* scenario flows.

Table 1 – Inventories used in the three scenarios (inputs and outputs).

Item	CT_Base	CT_Solar	CT_Reuse
Inputs			
BOD_5 (kg)	63,587,377,14	63,587,377,14	63,587,377,14
COD (kg)	120,657,118,07	120,657,118,07	120,657,118,07
N-NH_4 (kg)	7,345,325,85	7,345,325,85	7,345,325,85
S Sed (kg)	708,702,25	708,702,25	708,702,25
SST (kg)	49,609,157,71	49,609,157,71	49,609,157,71
Total P (kg)	969,803,08	969,803,08	969,803,08
Chemical products (kg)	10,950,00	10,950,00	10,950,00
Water (kg)	4,500,000,000,00	4,500,000,000,00	4,500,000,000,00
Energy (KWh)	36,096,924,60	36,096,924,60	36,096,924,60
Outputs: emissions to the receiving environment			
BOD_5 (kg)	14,622,896,04	14,622,896,04	10,978,916,89
COD (kg)	34,630,431,59	34,630,431,59	25,972,823,69
N-NH_4 (kg)	3,777,252,46	3,777,252,46	2,832,944,00
S Sed (kg)	124,763,30	124,763,30	93,571,85
SST (kg)	11,376,536,17	11,376,536,17	8,532,402,12
Total P (kg)	708,702,25	708,702,25	531,526,69
Outputs: emissions to the soil			
Dry sludge (kg)	4,752,000,00	4,752,000,00	4,752,000,00
Sand and coarse solids (kg)	13,789,800,00	13,789,800,00	13,789,800,00
N-NH_4 (kg)	-	-	944,314,67
SST (kg)	-	-	2,844,134,039
Total P (kg)	-	-	177,175,56
Outputs: air emissions (from biogas)			
Particulate matter (kg)	151,338,00	151,338,00	151,338,00
CH_4 (kg)	16,046,511,01	16,046,511,01	16,046,511,01
CO (kg)	468,237,00	468,237,00	468,237,00
CO_2 (kg)	84,546,000,00	84,546,000,00	84,546,000,00
SO_2 (kg)	617,793,00	617,793,00	617,793,00
NO_X (kg)	284,427,00	284,427,00	284,427,00
Outputs: air emissions (from Transportation)			
Particulate matter (kg)	163.40	163.40	154,026,39
CO (kg)	3,305,09	3,305,09	3,115,533,73
CO_2 (kg)	237,669,12	237,669,12	224,038,380,38
SOx (kg)	209.82	209.82	198,308,97
NO_X (kg)	2,413,83	2,413,83	2,275,389,80

Table 2 – Magnitude of environmental impacts using the CML-IA baseline method.

Category of impact / Unit	C_Base		CT_Solar		CT_Reuse	
Abiotic depletion (kg Sb eq)	0.054	0.18%	30,30	100.00%	0.054	0.18%
Abiotic depletion (fossil fuels) (MJ)	1,693,242,727.96	100.00%	92,759,421.93	5.48%	1,693,242,727.96	100.00%
Acidification (kg SO_2 eq)	1,585,602.00	58.25%	926,497.17	34.04%	2,722,089.99	100.00%
Eutrophication (kg PO_4 eq)	2,777,384.46	59.37%	-1,043,153.78	-22.30%	4,678,163.26	100.00%
Aquatic ecotoxicity (freshwater) (kg 1,4-DB eq)	235,245.63	31.14%	755,562.98	100.00%	235,245.63	31.14%
Global warming (GWP100a) (kg CO_2 eq)	226,673,840.51	50.32%	94,294,650.93	20.93%	450,474,551.47	100.00%
Human toxicity (kg 1,4-DB eq)	13,817,738.31	82.88%	3,543,907.55	21.26%	16,671,477.12	100.00%
Aquatic ecotoxicity (marine water) (kg 1,4-DB eq)	18,076,369,290.00	100.00%	2,724,837,178.72	15.07%	18,076,369,290.00	100.00%
Ozone depletion (ODP) (kg CFC-11 eq)	9.07	100.00%	0.65	7.16%	9.07	100.00%
Photochemical oxidation (kg C_2H_4 eq)	80,206.38	1.31%	44,460.08	0.73%	6,129,153.41	100.00%
Terrestrial ecotoxicity (kg 1,4-DB eq)	62,601.13	100.00%	19,190.1	30.65%	62,601.13	100.00%

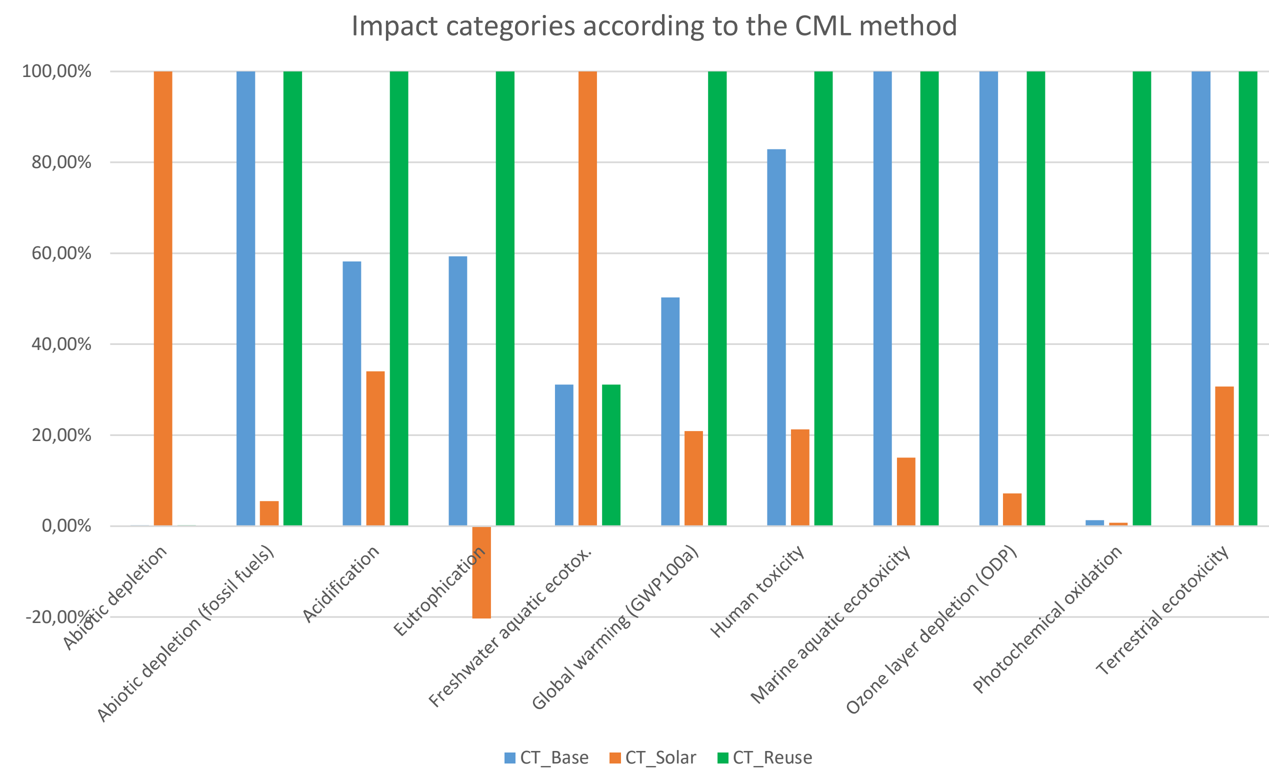

Figure 6 – Impact categories according to the CML method.

Table 3 – Magnitude of environmental effects using ReCiPe 2016 Midpoint (H).

Category of Impact / Unit	CT_Base		CT_Solar		CT_Reuse	
Particulate matter formation (kg $PM_{2.5}$ eq)	380,569.15	55.31%	221,788.02	32.23%	688,045.26	100.00%
Fossil resource depletion (kg oil eq)	35,237,256.80	100.00%	2,036,400.26	5.78%	35,237,256.80	100.00%
Freshwater ecotoxicity (1,4-DCB)	8,754.72	27.81%	31,485.17	100.00%	8,754.72	27.81%
Freshwater eutrophication (kg P eq)	261,646.16	57.31%	261,730.28	57.33%	456,539.28	100.00%
Global warming (kg CO_2 eq)	228,323,755.32	50.50%	94,406,861.65	20.88%	45,212,4466.28	100.00%
Human carcinogenic toxicity (kg 1,4-DCB)	84,092.79	35.18%	239,022.03	100.00%	84,092.79	35.18%
Human non-cancer toxicity (kg 1,4-DCB)	13,921,037.11	100.00%	3,958,932.58	28.44%	13,921,037.11	100.00%
Ionizing radiation (kBq Co-60 eq)	5,403,470.92	100.00%	1,501,009.75	27.78%	5,403,470.92	100.00%
Land use (m^2a crop eq)	0.00	0.00%	22,640.31	100.00%	0.00	0.00%
Marine ecotoxicity (kg 1,4-DCB)	64,160.12	84.72%	75,728.21	100.00%	64,160.12	84.72%
Marine eutrophication (kg N eq)	1,056,870.72	-73.33%	-1,055,982.89	-73.27%	1,441,233.21	100.00%
Mineral resource depletion (kg Cu eq)	24,293.25	32.73%	74,228.59	100.00%	24,293.25	32.73%
Ozone formation, human health	484,963.81	17.58%	306,459.56	11.11%	2,757,939.78	100.00%
Ozone formation, terrestrial ecosystem (kg NOx eq)	486,586.31	17.63%	306,954.45	11.12%	2,759,562.28	100.00%
Depletion of stratospheric ozone (kg CFC11 eq)	20.99	100.00%	3.92	18.67%	20,99	100.00%
Terrestrial acidification (kg SO_2 eq)	1,306,034.99	56.24%	755,516.32	32.53%	2,322,405.50	100.00%
Terrestrial ecotoxicity (kg 1,4-DCB)	82,149,670.70	88.37%	92,962,980.89	100.00%	82,149,670.70	88.37%
Water consumption (m^3)	-277,453.10	0.00%	-14,089,200,504.24	-100.00%	-277,453.10	0.00%

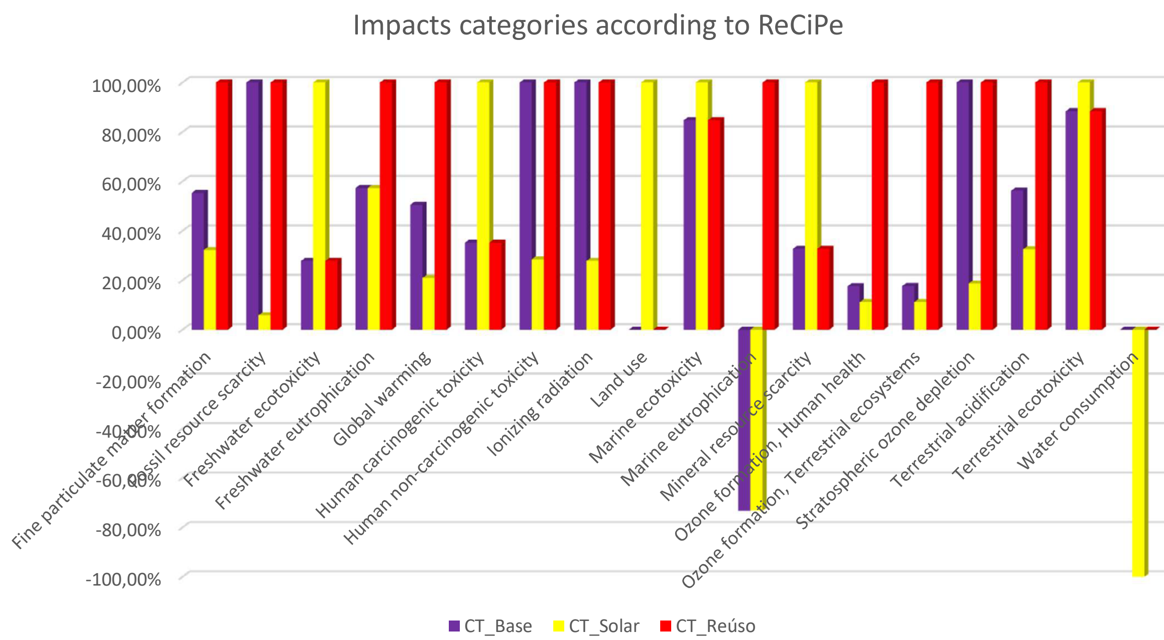

Figure 7 – Impact categories according to ReCiPe.

Souza et al. (2021) and Jamaludin et al. (2024) demonstrated that this type of WWTP has a high energy demand, primarily driven by aerators. Approximately 65% of the total consumption is attributed to these units. Therefore, the fact that the *CT_Solar* scenario uses a solar energy matrix rather than a water-based one explains the reduction in impacts across various categories. Batool et al. (2023) concluded that adopting measures to improve energy efficiency in this type of WWTP not only decreases O&M costs but also results in several environmental benefits, such as the reduction of greenhouse gas emissions.

Also, using this method, in no impact category was the *CT_Base* scenario the most impactful on its own. Therefore, it can be observed that the ReCiPe and CML-IA methods show significant convergence, especially regarding the identification of the most and least impactful scenarios.

Conclusions

Among the three scenarios simulated in this work, the *CT_Solar* scenario was the least impactful in most impact categories, according to both the CML-IA baseline method and the ReCiPe 2016 Midpoint (H). The impact categories analyzed in the first method included abiotic depletion of fossil fuels, acidification, eutrophication, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation, terrestrial ecotoxicity, abiotic depletion, and freshwater aquatic ecotoxicity. Only in the last two categories did the *CT_Solar* scenario demonstrate the highest impacts.

Regarding the ReCiPe method, the *CT_Solar* scenario was the most impactful in six of the 18 categories analyzed: freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, human carcinogenic toxicity, land use, and mineral resource scarcity. The fact that the boundary delineation of each scenario includes the manufacturing phase of the photovoltaic modules (from the mineral extraction stage) significantly contributed to amplifying these impacts.

In all analyses conducted, the *CT_Base* scenario did not have a greater impact than the *CT_Reuse* scenario in any impact category. In the latter scenario (*CT_Reuse*), the transportation phase using water trucks for the required amount of reuse contributed significantly to the intensification of impacts across various categories, making its adoption not advisable in a sustainable scenario.

Given the facts mentioned above, the importance of applying the LCA methodology in WWTPs is highlighted. Through simulations of alternative scenarios, this approach allows managers––such as directors of sanitation companies, regulatory agencies, or government bodies related to the subject––to confidently select the most sustainable scenario. This decision, based on LCA, not only analyzes the discharge patterns of the effluent into the receiving body but also considers the entire global chain of impacts generated throughout the life cycle of the WWTP.

Finally, this research also contributes to filling significant gaps in the literature by incorporating the manufacturing stage of photovoltaic technologies and the impacts of transportation on effluent reuse. Additionally, it identifies opportunities for future investigations that could include, for example, end-of-life analyses of the systems, different reuse modalities (such as industrial reuse), and complementary approaches like cost–benefit analyses, in order to deepen the understanding of the technical and environmental feasibility of the evaluated alternatives.

Authors' Contributions

Souza, B.M.: Conceptualization, data curation, formal analysis, funding, acquisition, investigation, methodology, writing––original draft, and writing––review and editing. **Oliveira**, R.: Project administration, resources, supervision, validation, visualization, and writing––review and editing. **Nascimento**, R.S.: Project administration, resources, software, supervision, validation, and visualization. **Medeiros**, K.T.B.: Writing––review and editing.

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