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Life Cycle Assessment of Wastewater Treatment in a Refinery with Focus on the Desalting Process

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Abstract: During refining operations, desalting wastewater provides 10-30% of the total wastewater volumes and contains 40-70% of the pollutants in the wastewater treatment unit. Desalting consists of removing impurities from the crude oil with washing water. The discharge of treated water into the receptor environment is controlled according to standards regulation. However, due to human health and environmental risks, a multi-criteria and multi-stage analysis must be carried out. This present study aims to identify critical sources of wastewater treatment impacts from desalting operations. Life cycle assessment (LCA) with LCIA methods namely Recipe, CML-IA, TRACI, and USETOX were used in Gabi Software. According to this study, fossil fuel-based, electricity generation is the major contributor to negative output flows with about 99%. Emissions of CO_2, CO, NOx, SOx, and COV during electricity generation influence the global warming potential through the greenhouse effect, acidification potential that causes acid rains, and photochemical oxidation potential relative to smog. Uncertainty relative to toxicity results does not allow conclusive points to be made. The inclusion of the desalting process in LCA of wastewater treatment is relevant for a comprehensive analysis. The preliminary results obtained during this work will be used in future LCAs in Africa to develop an environmental assessment database.

Key words: Life cycle assessment, wastewater, desalting process, refinery.

Introduction

The global market for petroleum products has been undergoing rapid evolution in recent years from emerging and developing economies, driven by rising populations and incomes. In Africa, crude oil distillation capacity has been estimated at 3.8 million barrels per day in 2020 (WOO, 2020). Oil refineries produce large amounts of wastewater estimated to be 0.4 to 1.6 times the amount of crude oil processed (Coelho et al., 2006). As a result, globally a total of 32.8 million barrels per day of effluent was generated in 2019, treated, and discharged into the receiving environment (Gao et al., 2018). Storage and refining processes including desalting produce salty wastewater, which is probably the most polluted water in the refinery (BAT, 2015). Of all refinery processes, desalting wastewater provides 10-30% of the total wastewater volumes and contains 40-70% of the pollutants in the refinery wastewater treatment unit (Chapelle, 1993). The desalting process favours the presence of polar organic compounds (Pak and Mohammadi, 2008), chemical pollutants such as

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ammonium, hydrogen sulfide, phenols, chloride, and, biological and physical substances in wastewater that are treated in WWTP (IPIECA, 2010). Evaluation of environmental impacts in wastewater treatment plants (WWTP) is essential because of the consequences of substances emissions in the environment.

There are several environmental impact assessment tools; however, Life Cycle Assessment (LCA) remains the more effective due to its multi-stage and multi-criteria characteristics. LCA is a decision support tool that analyses operational scenarios in WWTP by identifying critical sources (Muñoz et al., 2020; Lundin et al., 2000; Vlasopoulos et al., 2006; Niero et al., 2014). Godin et al. (2012) proposed LCA of WWTP, based on Net Environmental Benefit to assess the potential impact of releasing wastewater without and with treatment. Hospido et al. (2008) compared four WWTP in Spain by performing normalisation with the CML method and Simapro 5.1 software.

Côte d'Ivoire is one of the refiner countries in Africa through the Société Ivoirienne de Raffinage, located in the coastal area of Abidjan. This is a low-relief area with a low-lying coastline. The climate is Attiéen or equatorial with two rainy seasons and two dry seasons. The refinery was established in 1952 and has three large crude oil processing units that produce large quantities of wastewater that are treated at the wastewater treatment plant. Despite environmental regulations, from cradle to grave assessment is required to avoid emissions in the environment. This present research aims to identify critical sources of wastewater treatment impacts from desalting using the LCA method.

Materials and Methods

Life Cycle Assessment Methodology

Life cycle assessment is based on the ISO 14040, 2006 and ISO 14044, 2006 standardised method for assessing the environmental impacts of a process throughout its life cycle (Jolliet et al., 2010). The analysis consists of four steps: definition of the objective and scope of the study, inventory of data, evaluation of environmental impacts, and interpretation of results. The method reveals the potential sources of impact at each stage of the life cycle, allowing pollution displacement to be avoided, major contributors to environmental impacts to be identified and eco-efficient modifications to be made. GaBi software has been used for this analysis. GaBi databases supplied inventory data. Emission factors from European and Indian refineries were used. Impact indicators depend on the assessment method.

Nomenclature

Parameters	*Definitions*	*Units*
E_{VOC}	VOC Emission	(g)
Q	Emission factor	(g/m^2)
$Result_{cat}$	Impact category value	
$Result_{cat, ref}$	Impact category value in the reference system	
m_i	Magnitude or mass of emissions	(g)
$m_{i, ref}$	Magnitude or mass of emissions in the reference system	(g)

In this study, the Recipe method assessed three broad categories of impacts. These categories are (i) air quality related to emissions of GHGs or hazardous gases into the air, and included acidification potential, global warming potential, and photochemical oxidation potential; (ii) eutrophication related to phosphorus and nitrogen emissions in aquatic environments; (iii) toxicity corresponds to local impacts such as Marine Ecotoxicity Potential, Aquatic Ecotoxicity, Terrestrial Ecotoxicity, Human Toxicity.

Scope of Study and Inventory Data

An LCA was carried out to analyse wastewater treatment from desalting in a refinery located in Abidjan, Ivory Coast. Three main stages of the system were identified: (i) desalting, (ii) stripping, and (iii) wastewater treatment (Figure 1).

Demineralised water, fuel oil, steam, and electricity generation represented utilities of the whole system. The demineralised water from the M'Bakré lake borehole was treated and used as a component of wash water to produce steam for the boilers. The fuel oil obtained from the heavy residue of the distillation column was burned in the boilers. Steam was used for stripping wastewater. Finally, electricity is produced by the steam passing through the turbines and supplies the entire refinery. Petroleum was mixed with wash water consisting of

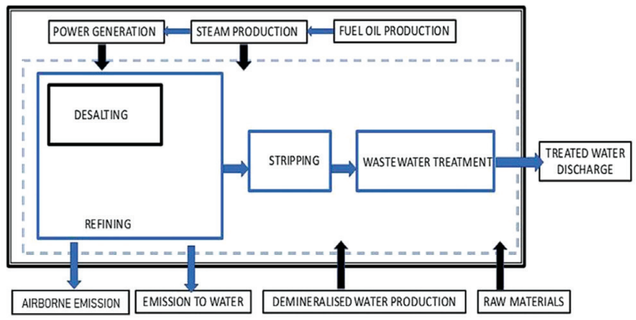

Figure 1: Crude oil desalting process system setup.

stripped process water and demineralised water. In each distillation unit, a crude oil throughput of 250 tonnes per hour generated about 20.5 tonnes of wastewater after passing through the desalter. Salty wastewater was pretreated with steam of 0.5 bar in a stripping column to remove light pollutants. Pretreated wastewater was collected, physically and chemically treated to be discharged at a rate of 20 tonnes per hour into the marine environment by environmental standards.

Data for this study were collected from different sources. The primary data was collected from the refinery's operational documentation (Report SIR, 2019). Indeed, the flow rates, temperatures, pressures, density, viscosity, and lower calorific value of fossil resources were taken from the operating documents of units. The levels of chemical pollutants such as ammonium, hydrogen sulphide, phenols, and chlorides in the crude oil and wastewater were determined with laboratory analysis results over one year by spectrometric essay, dosage, and distillation.

Secondary data were collected from the literature (BAT, 2015): (i) chemical compositions of crude oil, fuel oil, heavy residue, and, wastewater from desalter, (ii) inventory of electricity generation based on heavy fuel oil, and (iii) gaseous emissions. Safety data sheets of chemical manufacturers were used to determine the exact composition of the chemicals (Suez Water Technologies).

The system included water demineralisation, heavy fuel oil production, steam production, electricity generation, crude oil purification from the three treatment units, steam stripping, desalter outlet wastewater, and refinery wastewater treatment. The functional unit of study corresponded to the crude oil throughput of each three processing units at 250 t/h. The three stages of the system's life cycle were desalting, stripping, and wastewater treatment. (a) The desalting stage included associated processes, (b) the stripping stage included support processes and (c) the Wastewater treatment stage.

Mass and energy flows in and out of the system were considered. The quantification of VOC emission at the wastewater treatment unit was done using formula (1):

$$E_{VOC} = \text{exhibition area} \times q \quad \text{with}\; q = 20\left(\frac{g}{m^2}\right) \qquad (1)$$

Environmental loads of flows were calculated using data from the Gabi software database with the help of mathematical models from the Recipe method.

$$\text{Result}_{cat} = \sum m_i \times \text{characterisation factor}_{i,cat} \qquad (2)$$

Normalisation was carried out according to world criteria to compare environmental impact results.

$$\text{Result}_{cat} = \sum m_{i,ref} \times \text{characterisation factor}_{i,cat} \qquad (3)$$

$$\text{Normalised Result} = \frac{\text{Result}_{cat}}{\text{Result}_{cat,ref}} \qquad (4)$$

The characterisation factor defines the relative importance of substances emission for a specific impact category. Normalisation is combined with weighting for a fair assessment of environmental impacts. Life Cycle Impact Assessment (LCIA).

LCIA quantified the environmental impacts by converting the inventory data using algorithms and indicators. ReCipe 1.08 was used for assessment through weighting and normalisation (Goedkoop et al.. 2009). Other methodologies such as (i) TRACI 2.1, (ii) Recipe 2016 midpoint, (iii) USETOX and (iv) CML 2001 January 2016 were used to justifyRecipe 1.8 (H) results. The results of the assessment considered eight impact categories regrouped into three main categories: toxicity, air quality, and eutrophication.

Results and Discussion

Life cycle impact assessment results presented three portions of environmental impact categories based on ReCiPe 1.08 Midpoint (H).

A score of each impact category was first divided by a reference of choice or linked to the annual environmental average load in an area and then divided by the number of inhabitants quantifying this impact category. The weighting factor depends on the assessment method (Bengtsson and Steen, 2004). Normalisation provides an equivalent number of people for a given impact based on the impacts of activities of an average person in the world over a year.

Figure 2 shows the impact results of three main categories. Toxicity was the highest category at 54%. It was followed by air quality at 44% and eutrophication at 1%.

Global and Regional Impacts

Global impacts were represented by global warming and regional impacts by acidification, photochemical oxidation potential, and eutrophication.

Figure 4 showed that desalting utilities, specifically electricity generation, was the major contributor.

Weighting scores of marine and freshwater eutrophication were lower than those of air quality (Figure 3). Indeed, these low rates of eutrophication

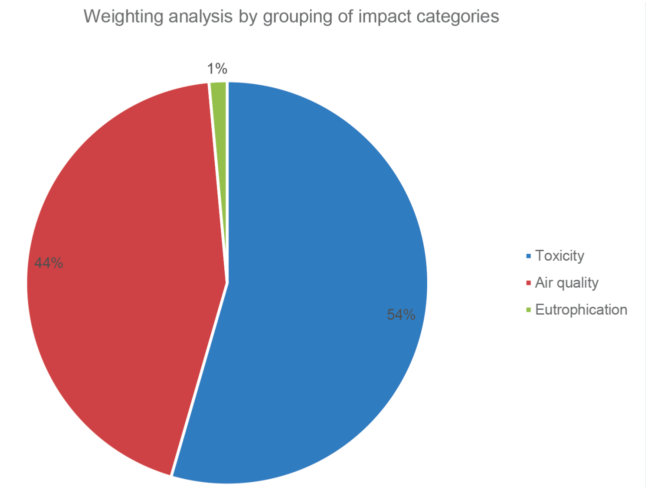

Figure 2: Life cycle assessment of grouped weighted impacts of the desalination process.

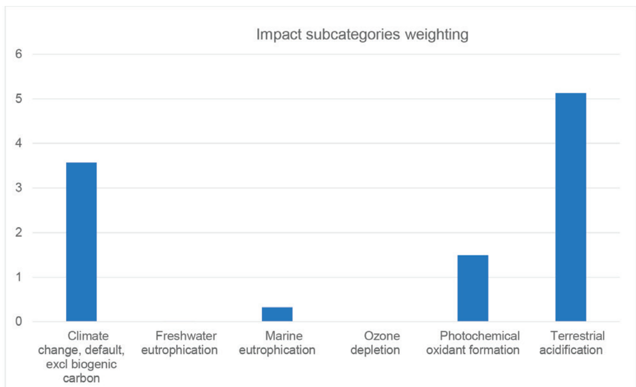

Figure 3: Recipe 1.08 midpoint (H) evaluation method of impact subcategories weighting for the desalination process life cycle assessment.

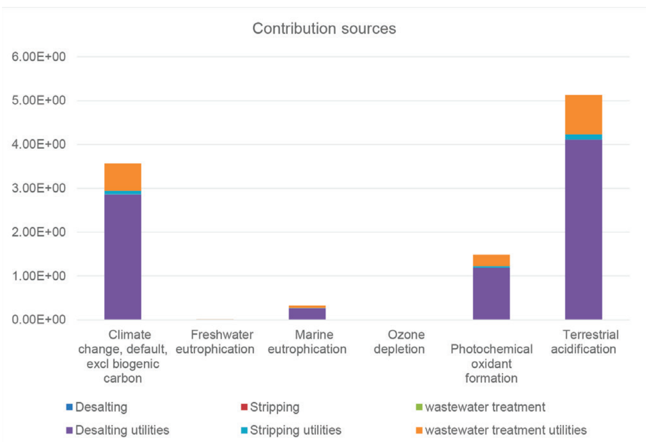

Figure 4: Sub-categories impacts sources in the life cycle assessment for the desalination process.

potential can be explained by the nutrient removal capacity of the wastewater treatment system.

Air quality, represented by acidification potential (AP), global warming potential (GWP), and photochemical Oxidation Potential (PO) had greater scores than 1 (Figure 3). Global warming was expressed in kilograms of CO_2 equivalent (kg CO_2eq), acidification potential in kg SO_2eq, and photochemical oxidation potential in kg VOCeq or kg NOeq. Critical sources of these three sub-categories of impacts were energy consumption during pumping and equipment aeration, and electricity generation through turbines and motors. The combustion of heavy fuel oil was used to heat demineralized water in boilers to produce steam and then electricity is produced using turbo generators. Power plants, boilers, and heaters were emitters of pollutants such as carbon monoxide and carbon dioxide (CO, CO_2), nitrogen oxides (NOx), particulate matter, sulfur oxides (SOx), and VOCs into the atmosphere. CO_2 and SOx emissions depended on the sulfur and carbon content of heavy fuel oil (BAT, 2015).

Several authors have demonstrated through their studies that electricity generation is the source of environmental problems such as global warming, acidification, and photochemical oxidation potential (Emmerson et al., 1995; Wang et al., 2019). Figure 5 shows a comparison of Li et al. (2013) using the CML 2000 method and an actual study with the Recipe 1.08 method. The contribution of electricity generation remained above 75% in both analyses. These results confirmed that the results of this study matched those of the literature (Gallego-Schmid and Tarpani, 2019; Hospido et al., 2008; Niero et al., 2014; Wang et al., 2019).

Global warming potential (GWP) measures the contribution of greenhouse gases to global warming

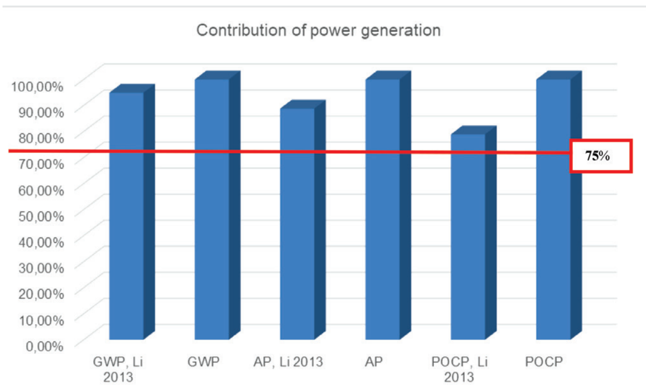

Figure 5: Power generation contribution results comparison.

according to indicators proposed by the scientific community of the IPCC (International Panel on Climate Change). GWP score varied between 2642 and 2682 (kg CO_2eq) (see Figure 6) depending on the assessment method. The values of each method were close enough with a relative difference of 2% to validate the results. The contribution of electricity generation was identical with all methods. NH_4 and CO_2 were emitted during heavy oil combustion. Electricity production for desalting operations contributed 83% (Figure 7).

Acidification potential (AP) refers to the loss of nutrients such as calcium, magnesium, or potassium due to SO_2, nitric oxide, and NO_2 or NH_3 emitted during operations. AP score varied from 30 to 37 (kg SO_2eq) (Figure 8) depending on the assessment method. Although the scores were more or less similar with a relative difference of 9% and 21%, the result is acceptable. The contribution of electricity generation was the same with methods. It is explained by excess emissions such as H_2S, HCl, SO_2, and NOx to air through electricity generation. The characterisation factor used by each assessment method resulted in different scores. Electricity generation for desalting operation and wastewater treatment especially reactor aeration was, respectively, 82.5% and 17.5% (Figure 9).

Photochemical reactions occur from the emission of NOx, SOx, and VOCs during combustion of heavy fuel oil, wastewater treatment, or accidental product leaks, in the presence of solar radiation, and lead to tropospheric ozone formation (O_3) and oxidizing compounds. Figure 10 shows electricity generation and wastewater treatment as major contributors. Recipe considered electricity generation as a major contributor because NOx and VOCs were emitted during heavy oil combustion. However, according to TRACI and CML2001, the main contributor was wastewater treatment due to VOCs emission at primary and secondary operations with open tanks and NOx, emitted during biological treatment (Ahn et al., 2010; Li et al., 2013). Characterisation factors influenced the identification of source contributors.

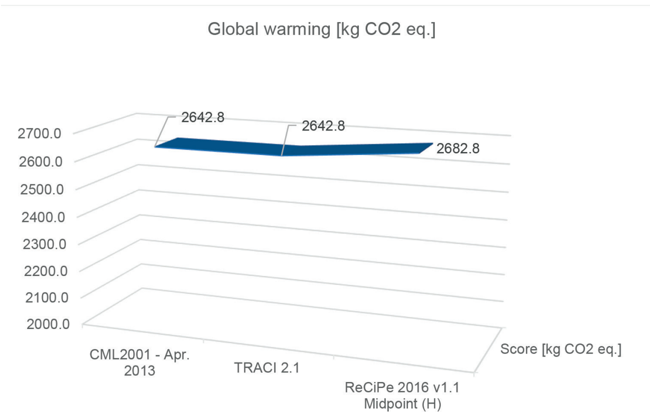

Figure 6: Global warming scores comparison by CML 2001, Recipe and Traci methods.

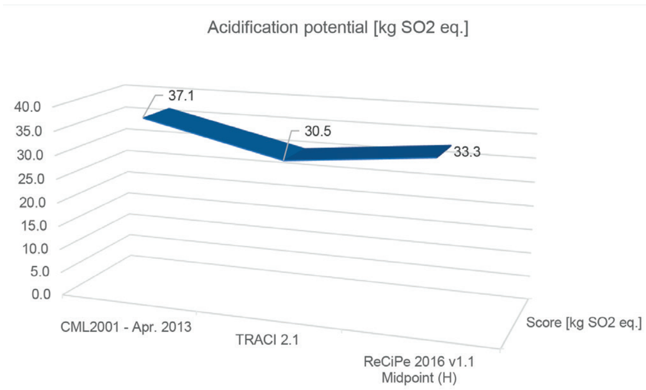

Figure 8: Acidification potential scores comparison by the CML 2001, the Recipe, and the Traci method.

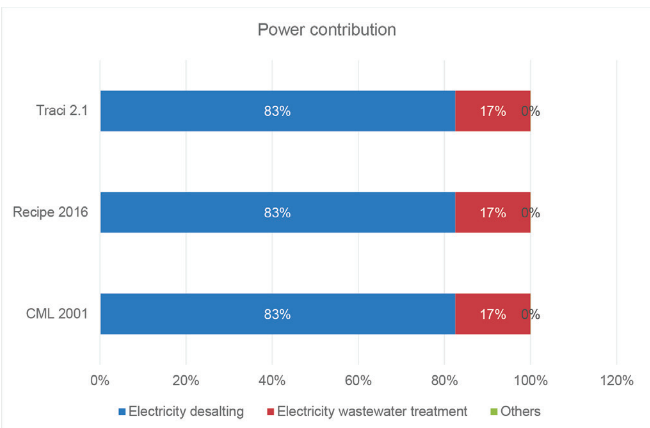

Figure 7: Electricity contribution analysis by the global warming impact assessment method.

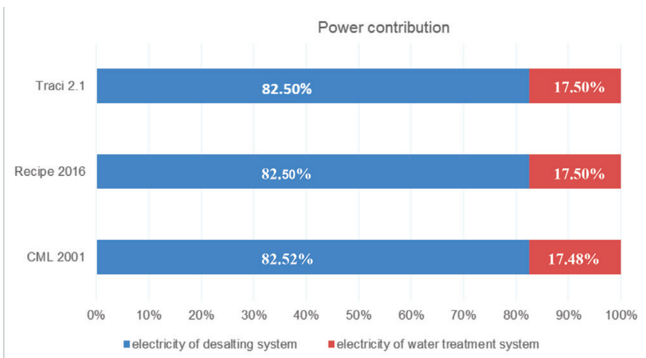

Figure 9: Electricity contribution to acidification potential impact analysis by life cycle assessment method.

Toxicity

Toxicity identifies chronic toxicological effects on human health and the ecosystem due to emissions of carcinogenic substances. Figure 2 showed toxicity as the critical impact category. The analysis of the results from the sources to the environmental impacts with assessment methods presents uncertainties. Figure 11 shows the sources' contributors changed according to

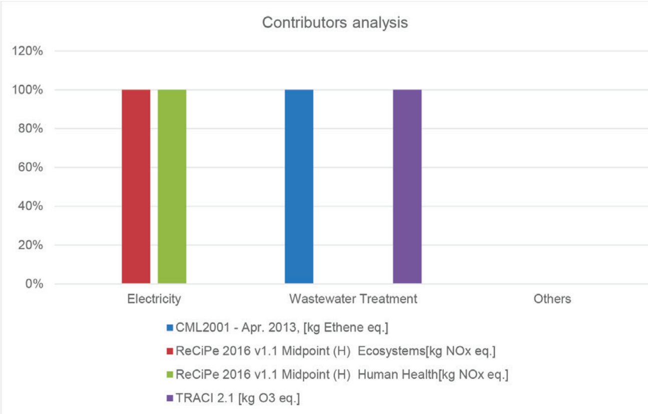

Figure 10: Photochemical oxidation potential contributors analysis by Life cycle assessment methods.

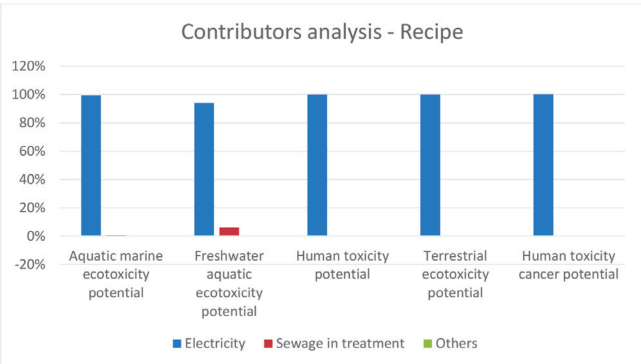

Figure 11 (a): Toxicity contributors analysis by life cycle assessment methods with ReCipe method.

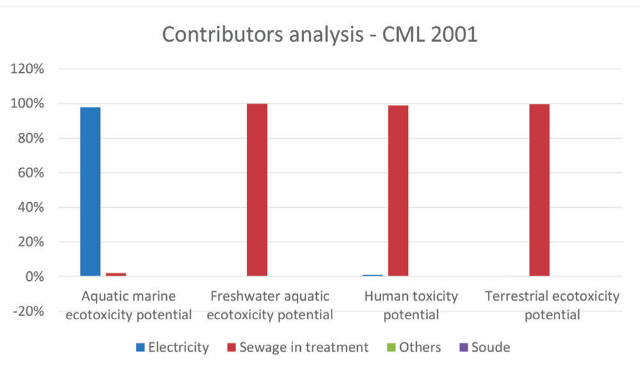

Figure 11(b): Toxicity contributors analysis by life cycle assessment methods with CML 2001 method.

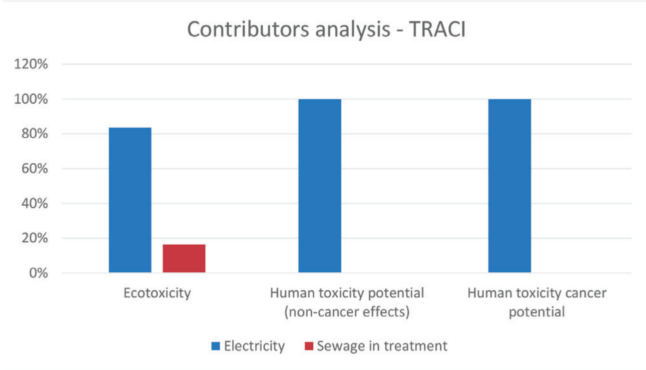

Figure 11(c): Toxicity contributors analysis by life cycle assessment methods with TRACI method.

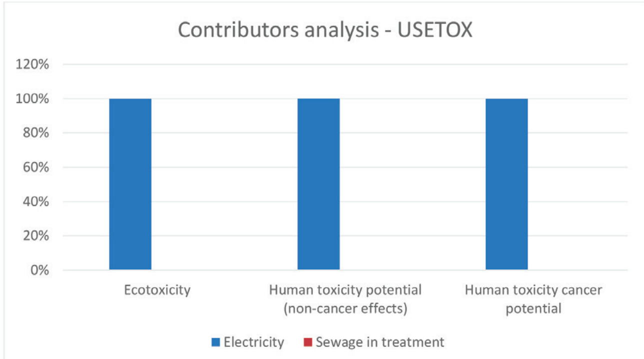

Figure 11 (d): Toxicity contributors analysis by life cycle assessment methods with USETOX method.

assessment methods. Recipe, TRACI, and USETOX methods indicated that heavy oil combustion produced the emission of metal ions such as cadmium, chromium, arsenic, copper, lead, and nickel into the atmosphere through the smoke. Whereas CML 2001 method presented sewage in treatment as a major contributor to freshwater and terrestrial ecotoxicity and human toxicity with 99% and electricity generation as the main contributor to aquatic marine ecotoxicity potential. Sludge from heavy oil combustion emitted metal ions that polluted marine and aquatic ecosystems (Huijbregts et al., 2005). Sewage in treatment was also presented as a contributor of 17% to ecotoxicity with TRACI and 6% to freshwater aquatic ecotoxicity potential with Recipe.

Toxicity results were subject to uncertainties due to variations in assessment methods. Renou et al. (2008) described these results as unacceptable given the different models available. Uncertainties in toxicity were subject to sensitivity studies between methods (Rashid and Liu, 2021). Rosenbaum and Bachmann (2008) suggested the use of the USETOX method (recommended by the UNEP SETAC life cycle initiative) whose characteristic factors used for human toxicity assessment and aquatic ecotoxicity are the result of comparison studies between several LCA models. Furthermore, Renou et al. (2008) proposed the integration of local parameters in models. Despite the uncertainties of results, the contribution of electricity generation on marine ecotoxicity and human toxicity should be monitored.

Conclusion and Recommendations

This work aims to assess the environmental impacts of wastewater treatment from the desalting process. The study has shown the great influence of the environmental impacts of electricity generation by fossil fuel combustion. The system required a large amount of energy, which resulted in huge emissions of polluting gases into the atmosphere. Emissions from electricity generation have contributed most to the global warming potential, acidification potential, and photochemical oxidation potential. However, the results on toxicity could not be affirmed because existing models do not allow for indisputable conclusions. Due to the particularity of the system studied, the most relevant emissions related to electricity generation were located in the desalting process. The inclusion of the desalting process in LCA of wastewater treatment is relevant for a comprehensive analysis. Furthermore, the life cycle assessment method is in full swing in Africa, and an application of LCA with fewer compromises linked to uncertainties requires the development of databases and evaluation methods that are in line with the realities of the continent (Karkour et al., 2021).

Conflict of Interest

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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