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Produced water treatment technologies: how to compare by LCA methodology

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ABSTRACT

Due to its complex and polluting composition, norms regarding the discharge of produced water into the environment have gradually become more and more limiting. The costs of appropriate produced water treatments amount to about 40 billion dollars per year and they weigh clearly on the price of final products. For a sustainable water use in the Oil and Gas sector, especially in arid places where water is a valuable and precious asset, it is necessary to reuse the water after a primary treatment. The aim of this work is to present a life cycle assessment (LCA) to highlight the importance of treating the produced water and to understand its importance from the environmental point of view. The LCA analysis compares 6 different processes of produced water treatment in order to find the best in terms of low environmental impact, with a special focus on effects on human health. The use of innovative biological treatments, such as the two phase-partitioning bioreactors, able to remove dissolved BTEX from produced water, appear to be a reliable solution to reduce the impact of produced waters treatment.

Keywords: Produced water; TPPB; Membrane; LCA

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1. Introduction

Now a days, oil plays a leading role in modern industrial society: it covers 40% of the world's energy demand and provides 95% of energy in the transport field [1]. Crude oil is a natural mixture of hydrocarbons, gathering in sedimentary rocks. Oil extraction leads to considerable amounts of liquid wastes, called produced waters. They account for around 70% of total oil production wastewaters volume and are characterized by a high content of salts and oil, which forces to draw a purposed treatment train, different, for example, from those commonly used for municipal wastewaters treatment [2].

Extraction technology and reservoir properties affect the amount of produced waters [3], with the water/oil volume ratio raising up to ten [4]. Produced waters have been in contact with hydrocarbons for millions of years and therefore it is very corrosive, biologically active and characterized by a very high salinity. Typically, produced waters contain high concentrations of aromatic hydrocarbons e.g., BTEX (benzene, toluene, ethylbenzene, xylene), NPD (naphthalene, phenanthrene e dibenzotiophene) and PAH (polycyclic aromatic compounds), minerals, radioactive substances, dissolved gases, scale products, waxes, microorganisms and dissolved oxygen. The organic content mainly consists of biorefractory compounds that can be hardly degraded by conventional treatment processes [5,6]. The salt concentration ranges between few and 300,000 mg L^{-1}; the total organic carbon (TOC) concentrations lie between 0 and 1500 mg L^{-1} and oil and gas (O&G) concentrations between 2 and 565 mg L^{-1} [7].

Due to its pollutant content, the normative regarding the direct discharge of produced waters into the environment is getting more and more limiting and stringent. The produced waters treatment strongly affects the final price of

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products. Moreover, in arid places, where water is a crucial asset, it is crucial to think about a reuse of treated produced waters.

Biotechnological treatment processes (bioremediation) represent a promising solution for water reclamation. In this work, we refer to the two phase partitioning bioreactor (TPPB) as central core of the biotechnological treatment. TPPB behaviour is based on the controlled release of substrate (xenobiotics present in the produced water which at high concentration inhibit biomass degradation rate) from the partition phase (represented in this study by a solid polymer) to the aqueous phase, containing the biomass able to degrade the substrate. The organic load at high concentration is thus initially stored in the partition phase and then gradually released into the aqueous phase; in this way the substrate inhibition effect on biomass is strongly reduced [8].

Life Cycle Assessment analysis is an elective methodology to assess the impact of production processes: the application to evaluate wastewaters treatment helped identifying the best trade-off between water quality and energy consumption, including the effect of deployed chemicals [9,10]. The current state-of-art points to LCA as an elective method to select between alternative schemes for water reclamation and reuse [11], which when coupled with other sustainability assessment, such as material flow analysis (MFA) and environmental risk analysis, plays a pivotal role in decision making framework [12]. However, the right choice of the impact methods are crucial to provide unbiased, reliable guidelines for wastewater treatment technologies [13].

In this work, we present a comparison of 6 produced waters treatment processes by means of a Life Cycle Assessment analysis, so to identify the best process in terms of low environmental impact. The assessment includes the entire life cycle of the process: the extraction and processing of raw materials, manufacturing, transportation, distribution, use, reuse, recycling and disposal.

In this work, we applied the LCA methodology by means of the process simulator Gabi 6. The six case studies under our analysis are:

1. No treatment;
2. Injection in existing wells;
3. Primary treatments, with transport;
4. Primary treatments, without transport;
5. Innovative biological treatment with two phases partitioning bioreactor (TPPB);
6. Bioreactor downstream processing with membranes.

The application of tertiary treatments (membranes) makes the produced water suitable not only for the disposal but also for direct applications in the civil and industrial field. In this way, treated produced waters may be turn into a value rather than only a waste [15–19]. The industrial world has been the promoter of water reclamation from waste sources to ensure the highest recyclable effluent ratio and to reduce the economic and the environmental impacts, mainly in the oil and gas sector where the economic value of the recycled water justifies the development of advanced technological solutions based on membrane filtration [20,21].

2. LCA Assessment

We report as follows the description and the boundary limits of the 6 produced waters treatment processes under analysis.

2.1. LCA methodology

The functional unit for all processes is 3500 m^3 of produced water, a typical output of a daily oil extraction from an oil & gasfield. The study is a "cradle-to-gate" LCA, covering all relevant steps from produced water extraction to the final water treatment.

To keep the study feasible yet realistic, it was mandatory to limit systems modelling details: the total cut-off was not more than 5% of input materials with respect to the functional unit.

The LCA analysis was performed by the "Gabi 6" LCA software, with a *mid-point* approach, including as impact categories: Global Warming Potential (GWP, kg of CO_2 equivalent); Acidification Potential (AP, kg of SO_2 equivalent); Fresh Water Ecotoxicity (FWE, kg of 1,4 DB equivalent), Eutrophication Potential (AP, kg of PO_4 equivalent); Ecotoxicity and Human Health, quantifying the effect of emissions derived from Ecosystem and Human exposure to produced water emissions, evaluated in CTUe and CTUh, which are, respectively, the number of animal species disappeared and the number of human cancer generated from the exposure to 1 kg of emissions derived from produced water; and fossil depletion (FD, kg of consumed oil equivalent). LCI data come from Gabi 6 library and have been partially integrated with literature data.

In the following paragraphs, we report a thorough description of the six case studies we analysed in the LCA study.

2.2. LCA case studies

2.2.1. Case study 1

The first case study describes the total absence of treatments and no re-injection (see Fig. 1): this solution, clearly not reliable and not compatible with EU directives and national laws, has been analysed to understand the polluting power of produced water and to set a blank case as reference for the other scenarios of our interest.

The untreated produced water is disposed in the environment, directly dumped as is in a river, by means of a pumping system absorbing 15 kW. The BTEX composition of the untreated produced water is reported in Table 1.

2.2.2.Case study 2

The second case study deals with the partial re-injection of produced water (see Fig. 2): it has been supposed that 2500 m^3 of produced water are re-injected into the extraction well, while the remaining 1000 $m^3$are disposed into the environment (river water). The pumping systems for water disposal in the river requires 5 kW, while the re-injection is accomplished by two injection lines, each fed by a multistage centrifugal pump absorbing 250 kW.

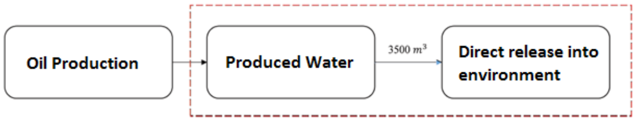

Fig. 1. Case study 1: no water treatments.

Table 1
BTEX composition [19]

Component	Lower value ($mg\ L^{-1}$)	Upper value ($mg\ L^{-1}$)
Benzene	0.032	15.00
Toluene	0.055	5.85
Ethylbenzene	0.086	0.56
m-Xilene	0.258	1.30
p-Xylene	0.074	0.33
o-Xylene	0.221	1.66
Total BTEX	0.730	24.10

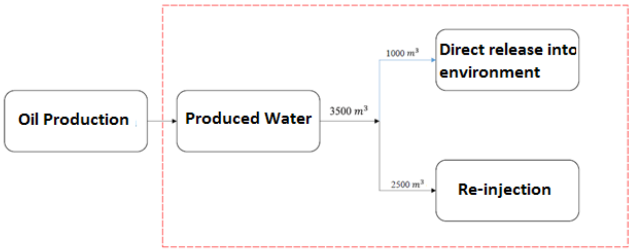

Fig. 2. Case study 2: well partial re-injection.

2.2.3. Case Study 3

Case study 3 is focused on primary treatments applied to produced water (see Fig. 3). Primary treatment plant includes an API Separator, a Flotation and a Metal Removal unit. The stream coming from primary treatments is always disposed in the environment (river water).

In the API Separator, it was assumed that the treatment takes place under the following ideal conditions:

- water passage is ensured by gravity;
- the only energy consumption of the separator is due to the skimmer, removing the sludge from the bottom. At this aim, it was assumed a circular tank with a diameter of about 10 m with a bridge scraper with central drive (engine power of 0.2 kW).

In the flotation unit, it was assumed that the particles do not require a flocculation process (due to their size), therefore the unit energy consumption is only due to:

- the skimmer, which, as in the previous case, serves to remove the sludge from the bottom, absorbing 0.2 kW;
- an air injector of hypothesized output of 27.3 kW.

For the metal removal unit, it was assumed the use of a mixer consuming 0.75 kW.

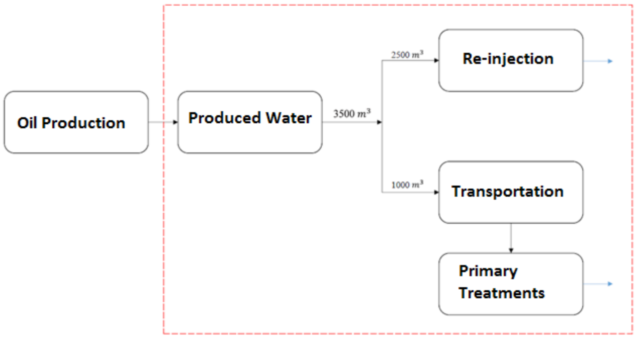

Fig. 3. Case study 3: Re-injection and primary treatments.

Table 2
Primary treatments efficiency

Treatment type	Removal efficiency (%)
API Separator	80% oil
	90% TSS
Flotation	90% oil
	90% TSS
	25% COD-BOD
Metal Removal Unit	5% TDS

Table 3
Water composition after primary treatments

Component	Water concentration (mg/l)
TSS	≈ 0
Total oil	<10
COD	2300
BOD	1100
TOC	1500
TDS	3500 ppm

We used literature data for the performance removal of the primary treatments plant [18] reported in Table 2, while Table 3 shows the produced water composition after the primary treatments [19].

In this scenario, we also analysed the influence of transportation facilities to move the produced water to the primary treatments plants far from the oil and gas plant (Table 4). Specifically, we assumed the transportation is carried out by tankers (Euro 3, diesel engine) with a load capacity of 27 tonnes.

2.2.4. Case Study 4

Case study 4 (not shown in the figure) is similar to case study 3 except for the transportation unit, not included in the analysis, in order to highlight the influence of transportation on the overall environmental impact of the process.

Table 4
Transportation details

Company location	Distance from oil and gas plant (km)
Lamezia Terme (CZ)	235
Bologna (BO)	740
Reggio Calabria (RC)	350
Bergamo (BG)	964
Matera (MT)	125

2.2.5. Case Study 5

Since primary treatments are able to remove suspended organics compounds in the produced water but are totally ineffective to remove dissolved BTEX, in the case study 5 (Fig. 4) we assume the presence of secondary treatment in series with primary treatments devoted to the BTEX removal. As secondary treatment we assumed to use a two-phase partitioning bioreactor (TPPB), supposed to work in no substrate inhibition conditions. The TPPB energy duty includes the mixer (0.75 kW) and air injection (75 kW) duties, respectively.

We introduced the removal efficiency of the TPPB as taken from literature [8] and reported in Table 5 in terms of produced water composition in BTEX after the TPPB treatment. The stream coming from secondary treatments is disposed in the environment (river water).

2.2.6. Case Study 6

Case study 6 (Fig. 5) introduces also tertiary treatments in series with primary and secondary treatments. The use of tertiary treatments (membrane-based in this case) are necessary to meet the law requirements for water reuse in the industrial (like cooling water) or agricultural fields (no food crops). Anyway, also in this last case, the stream coming from tertiary treatments is disposed in the environment (river water).

3. LCA results and discussion

In this section we report the LCA results (Figs. 6–12) for each case study grouped in seven impact categories, selected as representative: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ecotoxicity(E), human health(HH) fossil depletion (FD) and fresh water ecotoxicity (FWE). Due to data uncertainty (Table 6), we have identified the data affected from the major grade of uncertainty and in order to evaluate their effect on LCA results has been performed a sensitivity analysis. Therefore, for each impact category has been considered three different scenarios, the first one, called "mean value" refers to the average composition of produced water reported in Table 1 while scenarios 1 and 2 refer to half and double value of that reported in "mean value". As for processes energetic duty, scenarios 1 and 2 refer to a reduction and increase, respectively of 20% of energetic duty with respect to "mean value" as reported in the description of each case studies under analysis.

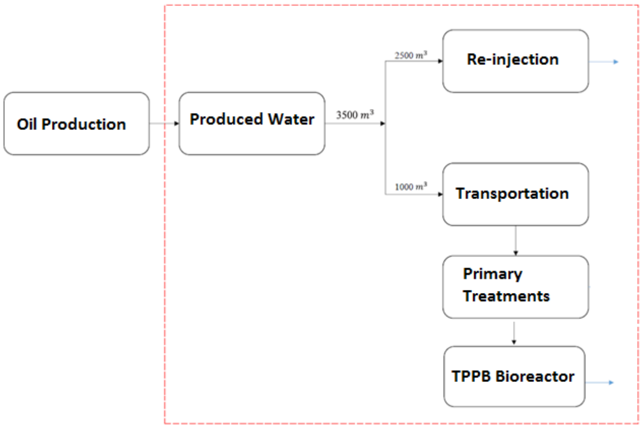

Fig. 4. Case study 5: TPPB Bioreactor. Note that case study 4 is similar to case study 5, except for transportation which is omitted.

Table 5
BTEX composition after TPBB reactor

Component	Concentration (mg/l)
Benzene	0.005
Toluene	0.004
Ethylbenzene	0.005
Total Xylene	0.0006

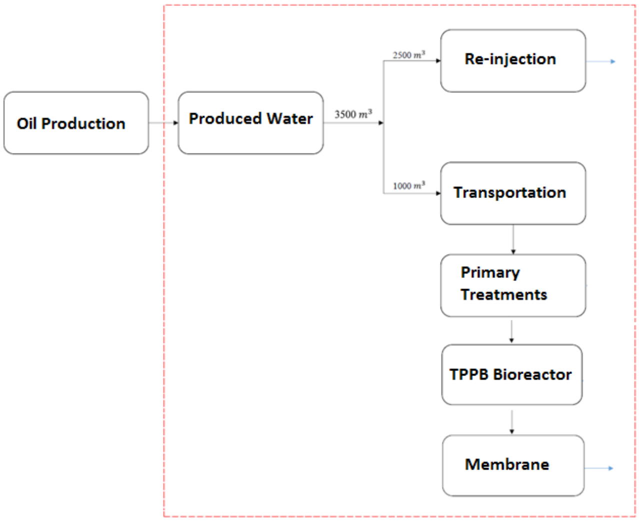

Fig. 5. Case study 6: TPPB bioreactor and membrane treatments.

Case study 1 shows a very high environmental burden for all the impact categories, not directly related to energy consumption, such as eutrophication, ecotoxicity, fresh water ecotoxicity and human health, while its impact on the global warming, acidification and fossil depletion is very low, due to the low energy duty (only for pumping systems).

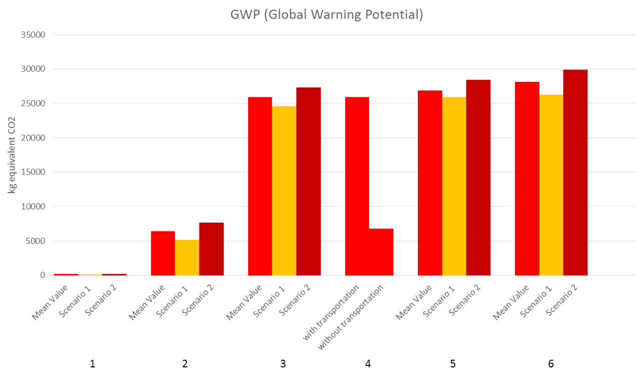

Fig. 6. Global warming potential.

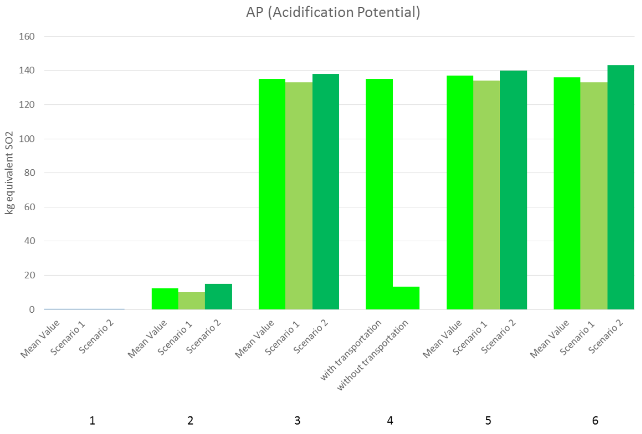

Fig. 7. Acidification potential.

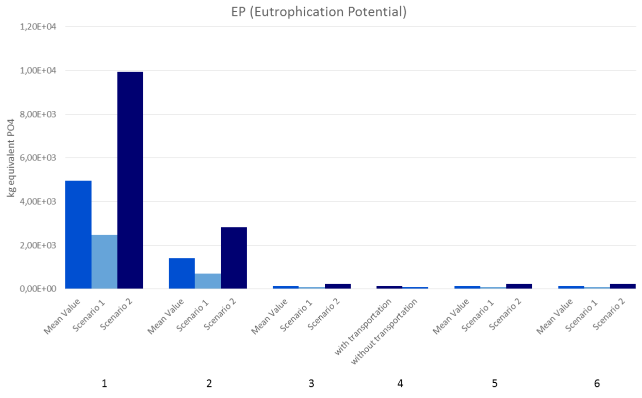

Fig. 8. Eutrophication potential.

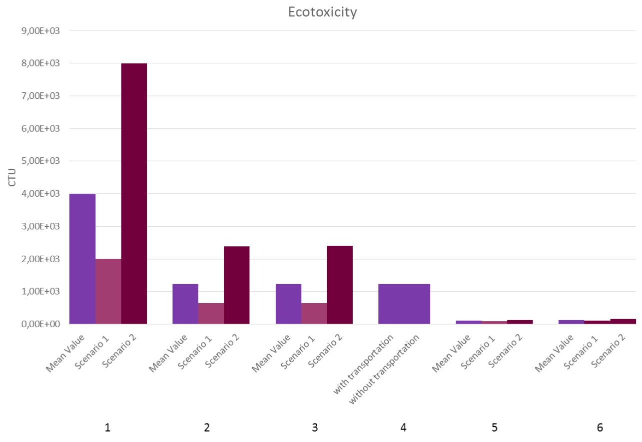

Fig. 9. Ecotoxicity.

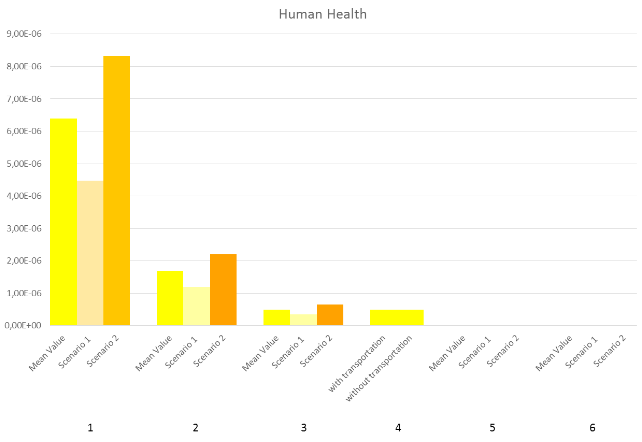

Fig. 10. Human health.

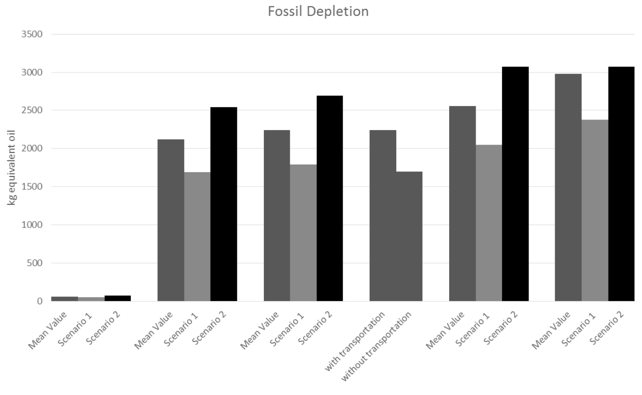

Fig. 11. Fossil depletion.

Fig. 8 highlights a strong reduction of the EP from case Study 2 to 3, which suggests that the introduction of primary treatments is a viable solution towards the environmental impact reduction of produced water treatment. However, a deeper analysis of the impact on human health, fresh water ecotoxicity and ecotoxicity suggests that the primary treatments are only a partial solution, since the overall environmental burden remains almost unchanged: primary treatments drastically reduce the organic and inorganic substances present in the produced water as suspensions, resulting into a lower nutrients release in the river, responsible of the Eutrophication Potential. On the other hand, these treatments are ineffective to remove soluble organic compounds, such as BTEX, which strongly impact on Human Health. It is also evident that the partially re-injection of produced water could be an effective solution to

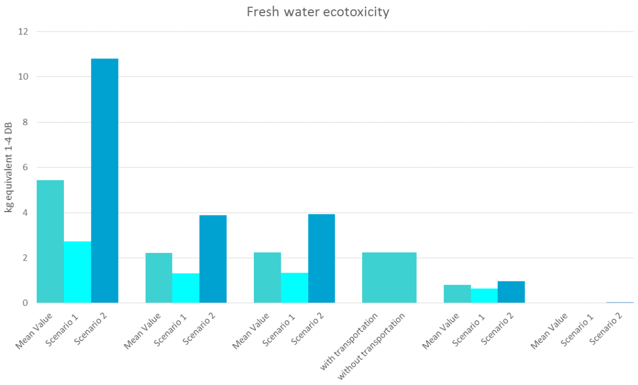

Fig. 12. Fresh water ecotoxicity.

Table 6
LCI data quality

Type	Value (%)
Measured	3.82
Calculated	24.4
Literature	63.9
Estimated	4.02
Unknown	3.92

reduce air emission, but if the final target is the preservation of human heath, it does not seem a viable solution as well.

The transportation impact for the case study 6, in terms of GWP, AP and FD, strongly affects the overall environmental impact of processes, but this effect is weaker on human health, ecotoxicity and fresh water ecotoxicity, since the BTEX load is far higher and predominant.

The global effect of BTEX is evident from the analysis of case study 5, since the use of secondary treatments (TPPB) strongly reduces BTEXs concentration and consequent noxious effects on the human health, ecotoxicity and fresh water ecotoxicity.

As key variable to quantify the effect of BTEX on Human Health and to assess the importance of BTEX removal, we computed the difference in human cancers occurrence due to exposure to BTEX emissions between case 1 and 5, for the duration of the entire life cycle of oil extraction (supposed 25 years): the introduction of biotechnological secondary treatments (TPPB, case study 5 and 6) reduces the percentage of cancer up to 99.98%.

Case study 6 is almost equals tocase study 5 in terms of environmental impact, but the introduction of tertiary treatment processes, such as the use of membranes, allows the reuse of treated water in the industrial field, i.e. cooling water, and in agriculture for irrigation purpose of no food crops.

4. Conclusions

In this work we compared the environmental impact of produced water treatment processes by means of the LCA methodology. Results have been given in terms 6 impact categories at *mid-point* level. Primary treatments are able to reduce the environmental loads related to organic and inorganic substances suspended in the produced water but are ineffective to remove BTEX dissolved in the same. Secondary treatments are mandatory to get rid of BTEX, specifically we demonstrated the use of the TPPB is a reliable and efficient solution, strongly reducing the environmental impact on Human Health. The use of tertiary treatments is required to treated produced waters reuse for industrial and agricultural purposes.

It is worth noting that due to the uncertainties associated with LCI data reliability and with LCA methods, the results reported in this work can be useful only to draw first considerations about the environmental reliability of produced water treatment processes.

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