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# Life cycle design and efficiency strategy for sustainable membrane technology

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**Abstract.** Life Cycle Assessment (LCA) is an assessment tool to evaluate the potential environmental impact of a system or product throughout its life cycle. Results from LCA provides an insight on developing a more sustainable system while identifying its environmental hotspots. With recent advancements in membrane treatment systems especially for wastewater treatment (WWT), there is a rising interest in its sustainability aspect. Thus, it is crucial to review on previous published studies to highlight the challenges and achievements in implementing LCA for the membrane system. Hence, this paper presents a review of 33 recent papers published from year 2017-2020 conducting LCA on membrane systems for WWT. Bounded by the key frameworks of ISO standards, the analysis of papers showed variance in defining its functional unit, system boundaries, impact assessment categories and method to evaluate LCA, which makes it a challenge to do comparison. Some of the challenges discussed and highlighted in this paper include the inconsistencies in specifying the impact assessment and methodology used for some journals and the lack of LCA study in certain regional areas. A more uniform implementation of LCA should be considered to ensure the reliability and reproducibility of results to allow adoptions on novel or existing membrane systems.

**Keywords:** Life cycle assessment, Environmental sustainability, Wastewater treatment, Membrane technology, Reverse osmosis

**Track Name:** Human, Social, Economic and Environmental Sustainability

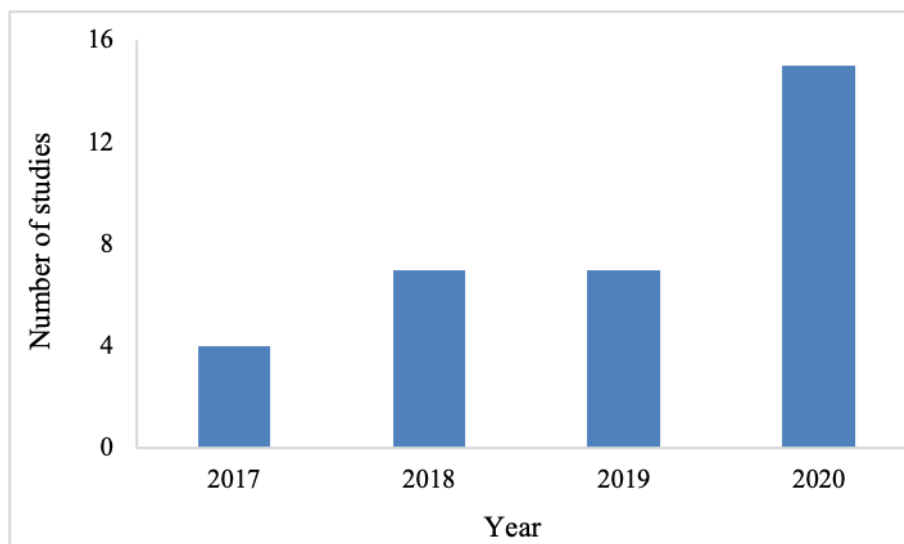
## 1. Introduction

Life Cycle Assessment (LCA) is a common tool utilised to analyse the environmental impacts associated with a system or product at all stages from its 'cradle-to-grave'. This includes the extraction of raw materials, product processing and manufacturing up to its final disposal. All the inputs and



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outputs of each process associated with the system are taken into account and its environmental impacts are assessed based on the International Standard Organization (ISO) 14040 series. The standardisation of the LCA framework begins in the late 1990s due to efforts made by certain governmental and international organisations to provide a guideline for LCA studies conducted [1][2]. The framework is guided by four fundamental phases; goal and scope definition, inventory analysis, impact assessment and interpretation [3]. With a proper framework, the comparison of studies is more objective and impartial allowing for a more reliable evaluation of the associated environmental impacts of a system. From the LCA results, improvements on the analysed system can be done and help in the decision-making process for future developments. Furthermore, LCA is a fairly versatile technique that aids in policy-making, as a marketing tool and for strategic planning [4]. The LCA approach is increasingly being used as a decision support tool in sustainable water management, providing valuable knowledge on the different environmental impacts of current or proposed water infrastructure and processes [5]. Membrane technology is significantly favoured due to the increasing complexity of wastewater contaminants and a great demand for wastewater reclamation to increase efficiency and reduce cost [5]. The technology relies on the concept of separation by removing specific contaminants from a solution or suspension through fluid passing by a membrane and retaining certain components. The scope of this analysis considers peer-reviewed journals, conference papers and chapters in books with a focus on membrane technology for wastewater treatment (WWT) system published from 2017 to 2020 as shown in Figure 1.



**Figure 1.** LCA studies on membrane technology by year (2017-2020).

LCA studies on membrane technology for WWT has seen an increasing trend generally (Figure 1) as sustainability is more incorporated into the design of membrane system. In the year 2020 alone, the LCA studies conducted are twice the number from previous years showing an increased interest in LCA as an evaluation tool. This number is projected to rise in the upcoming years as more policy-makers and organisations embrace to develop a more environmentally sustainable system for WWT and improve existing treatment systems.

## **2. Life cycle assessment methodology**

### *2.1 Goal and scope definition*

Various water treatment plants and systems were analysed in this paper with varying goals of studies. Some of the common goals defined were assessing the environmental impacts between different treatment systems or different scenarios implemented. The studies also managed to define the goal and

scope of the study to compare or evaluate different membrane systems or technologies that contributed to the lowest environmental impact. However, with various types of wastewater sources used for each study, the functional unit (FU) varies for different treatment systems [6] but commonly the FU is defined as 1 m<sup>3</sup> of treated wastewater. 91% of the studies explicitly defined the FU but 9% did not specify it. This existing variation affects making a reliable comparison among membrane treatment systems especially across the reviewed studies as different types of wastewater and FU were used for different systems. Nonetheless, the FU is unrepresentative as the quality of treated wastewater and its removal efficiency are not demonstrated [7].

In conducting an LCA study for a given system or product, there are many processes involved that are strongly interlinked together which complicates the starting and endpoint of evaluating the environmental impact. Hence, defining a system boundary is important as it sets a limit on what inputs and outputs to consider are relevant to the system. The most common system boundary defined by these LCA studies mainly concerned themselves on the construction and operation phase only. It is possible to identify other framework boundaries for LCA studies, such as cradle-to-gate studies that do not consider product distribution and use, but this depends on the study's objectives and the availability of data and/or impact assessment methodologies [3]. There is a limited number of studies doing a full LCA from 'cradle-to-grave' [6-11] as the infrastructure phase is considered negligible to the environmental impact. The final disposal phase and dismantling of a plant is also seldomly considered with only 18% taking it into account. Regardless, [12] argues that a full LCA analysis helps in determining the sustainability of the membrane system from the parameters at each stage.

## 2.2 Inventory analysis

The LCA software utilised in these studies was mostly Gabi as the preferred choice partly due to its ability to model each element in a system giving a broad life cycle perspective. SimaPro is followed closely as one of the highly preferred software as it has multiple databases and impact assessment tools with a powerful graphical interface that clearly displays processes having the greatest impacts [13]. As for GaBi, their database is tailored towards industrial processes and flows which can be observed from certain studies that utilise industrial wastewater [14-17]. Nevertheless, 15% of the LCA studies did not specify the software used to model their LCA which poses the inconvenience of making an objective comparison. The differences in the LCA software tool utilised also affect the result obtained due to differences in characterisation factors for each software tool [18]. From 85% of the studies that stated the software used, Gabi was chosen by 11 studies, followed by SimaPro (10), OpenLCA (5), EASETECH (1) and TOTAL (1).

## 2.3 Impact assessment

The related life cycle impact assessment (LCIA) methodology used for wastewater treatment systems were CML, ReCiPe and TRACI methodology.

*CML method* is an impact evaluation approach that limits quantitative modeling to early stages in the cause-effect chain. The results are categorized into midpoint groups based on common mechanisms (for example, climate change) or widely agreed groupings such as ecotoxicity [19].

*ReCiPe method's* main goal is to reduce a large number of life cycle inventory outcomes to a small number of indicator scores. The relative severity of an environmental impact group is expressed by these indicator ratings at two levels; 18 midpoint indicators and 3 endpoint indicators. The advantage of utilising ReCiPe is its comprehensive selection of effect categories at the midpoint level compared to other approaches [20].

*TRACI method* characterises factors for LCIA, industrial ecology and sustainability indicators. Through common equivalence units, the characterisation factors measure the possible impacts of inputs and releases on particular impact categories. Processes, goods, services, businesses, and societies all benefited from the TRACI approach [21].

From the 33 papers analysed, most studies stated the impact methodology used with 6 choosing CML, 6 ReCiPe and 8 TRACI (Table 1). As for the remaining 13 studies, mixed methodologies were incorporated or they were unspecified.

**Table 1.** LCIA methods used in previous LCA studies.

Method	Developer	User (Reference)
CML	Centre for Environmental Studies (CML), University of Leiden	[10] [14] [15] [22] [23] [24]
ReCiPe	RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft	[7] [25] [26] [27] [28] [29]
TRACI	U.S. Environmental Protection Agency (U.S. EPA)	[8] [9] [16] [30] [31] [32] [33] [34]
Mixed methodologies/Unspecified	-	[3] [6] [11] [17] [35] [36] [37] [38] [39] [40] [41] [42] [43]

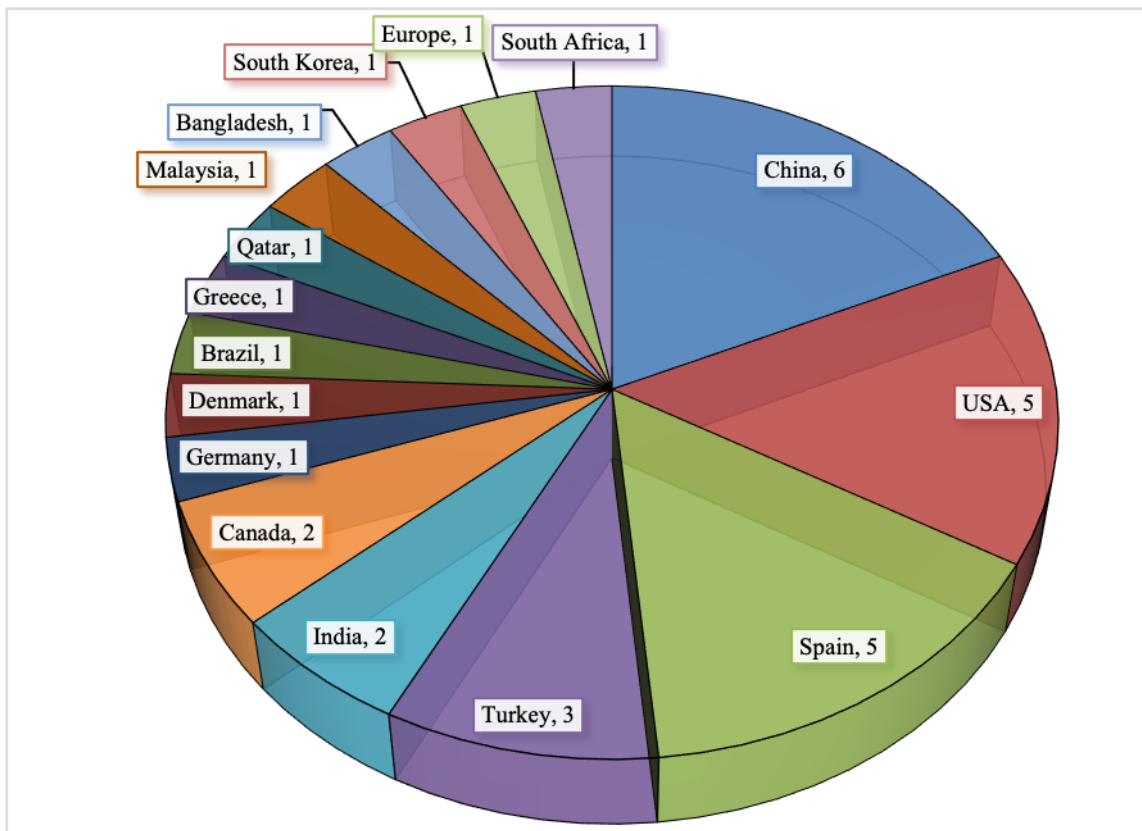
As for the impact category chosen, Global warming potential (GWP), Eutrophication Potential (EP) and Acidification Potential (AP) were frequently selected. [44] stated that GWP has the most potential to improve future environmental issues especially involving agricultural-based production. Only studies by [8] [32] [27] included all 18 impact categories for evaluation. Furthermore, the number of impact categories frequently included in these LCA studies were 10 impact categories including GWP, EP and AP.

#### 2.4 Interpretation

It has become critical to assess environmental performance using a validated and systematic approach such as the LCA [45]. Interpretation is an important step in the LCA as it provides a thorough and critical review on the analysed data. This is obtained from the result of life cycle inventory and impact assessment, where conclusions are made and stages of the systems that are contributing to the environmental hotspots are identified. From these information, the limitations of the system can be identified and suggestions are made for improvements in terms of sustainability. The key objectives of this step are to define possible areas for improvement, lend legitimacy to the LCA report, and prevent any bias arising from the practitioners' and/or organizations' personal interests and backgrounds [46]. The interpretation phase of the studies is further explored in the next section of this paper discussing the findings of the various membrane treatment system.

### 3. LCA of the wastewater treatment system

A comprehensive analysis was conducted on the reviewed studies to help identify and highlight the similarities and differences of LCA implementation for membrane systems in WWT along with achievements made. A total of 33 studies were reviewed within the year range of 2017 to 2020 with studies spread throughout the globe (Figure 2). While the collection of studies does not constitute a comprehensive overview of the field, they do represent the current state of the tool. The ISO framework also only provides a general methodology, the details and implementation of LCA for each membrane system differ from study to study. Through the ISO 14040/14044 guidelines, the environmental impacts were evaluated attributional as such.



**Figure 2.** LCA studies on membrane technology by country of origin.

The majority of the research evaluates various technologies of membranes, to determine which treatment systems or processes have the least environmental effect in treating wastewater. Two of the most frequently studied membrane systems are the membrane bioreactor and reverse osmosis. Wastewater treatment systems have been built and operated to manage water contamination and mitigate the environmental effects of industrial and domestic wastewater discharge, but they consume energy and chemical reagents, as well as generate sludge and other emissions [4].

### 3.1 LCA of membrane bioreactor in treating wastewater

A membrane bioreactor (MBR) combines membrane processes such as microfiltration or ultrafiltration with a biological treatment system and is frequently analysed in these studies to identify their environmental impact in a wastewater treatment plant (WWTP). Table 2 shows an overall summary of the LCA studies focusing on MBR treatment system including anaerobic membrane bioreactor (AnMBR), anaerobic fluidised membrane bioreactor (AFMBR), submerged membrane bioreactor (SMBR) and aerobic membrane bioreactor (AeMBR). The LCA studies primarily compare the environmental impacts of membrane bioreactors (MBR) and anaerobic membrane bioreactors (AnMBR) versus other treatment systems [3] [8] [41], with an emphasis on municipal wastewater and greywater treatment.

**Table 2.** LCA studies on MBR treatment system.

Reference	Goal	Source of water	Functional unit	Software
[3]	Compare three decentralised treatment system	Decentralised wastewater	1 m <sup>3</sup> of treated wastewater for irrigation	SimaPro
[6]	Compare three biological treatment system for non-potable reuse	Greywater	Delivery of non-potable reuse water for the whole building	Not defined
[8]	Evaluate full-scale AnMBR system	Urban wastewater	Volume of treated water (m <sup>3</sup> )	SimaPro
[9]	Evaluate greywater management system	Greywater	Annual treatment of greywater generated per person	OpenLCA
[15]	Assess two reclamation plant	Municipal wastewater	1 m <sup>3</sup> of reclaimed water	Gabi
[22]	Evaluate six wastewater treatment technologies	Municipal wastewater	1 m <sup>3</sup> of treated wastewater	Not defined
[25]	Evaluate integrated greywater treatment plant	Greywater	1 m <sup>3</sup> of treated greywater	Gabi
[28]	Evaluate three environmental technologies	Wastewater	10,000 m <sup>3</sup> /d of pre-treatment, biological treatment, disinfection, wastewater discharge and sludge treatment process.	Gabi
[29]	Evaluate four water management scenarios	Greywater	Undefined	SimaPro
[31]	Compare AnMBR-based treatment system to conventional treatment system	Domestic wastewater	Treatment of 5 million gallons of medium strength wastewater with the same effluent characteristics.	Not defined
[32]	Assess three treatment processes	Textile wastewater	1 m <sup>3</sup> of treated effluent	SimaPro
[33]	Evaluate treatment system as sewer mining water reclamation	Municipal wastewater	1 m <sup>3</sup> of treated wastewater	OpenLCA
[35]	Evaluate two separate treatment plants	Municipal wastewater	1 m <sup>3</sup> of treated wastewater	OpenLCA
[39]	Evaluate alternative ways of MBR treatment system	Dairy factory wastewater	1000 m <sup>3</sup> of treated dairy wastewater	EASETECH
[40]	Conventional activated sludge versus MBR	Hostel-site wastewater	1 L of treated or processed wastewater	SimaPro
[41]	Evaluate three greywater treatment system	Greywater	The same treated volume of greywater and the same amount of sodium dodecylbenzenesulfonate (SDBS) removed	Gabi
[42]	Evaluate membrane and conventional treatment system in given scenarios	Wastewater	Flow rate of wastewater (100,000 m <sup>3</sup> day <sup>-1</sup> ) for 20 years of operation	TOTAL

29% of the wastewater treated by the MBR system is greywater and [9] found that MBR is environmentally preferred especially when the reused greywater amount is larger. The anaerobic greywater reuse system is also shown to be the most eco-efficient as the system enables energy recovery giving an environmental advantage over the other systems [29]. In decentralised wastewater treatment, MBR technology is favoured more especially when there are fewer pollutant loads compared to conventional activated sludge (CAS) [40].

It can be concluded that the MBR treatment system is more environmentally feasible when compared to conventional treatment systems such as CAS. Depending on the type of wastewater being treated and the goal of the treatment, different types of MBR should be incorporated to ensure the least impact on the environment is achieved. [33] found that AnMBR when evaluated at all scales shows a net energy benefit. In treating textile wastewater, MBR is found to be the most efficient in organic compounds and colour removal but on the industrial-scale moving bed bioreactor (MBBR) is more attractive [32]. The drawback with using the MBR treatment system is its high energy consumption contributes to the environmental impact and proves to be a major environmental hotspot.

### 3.2 LCA of reverse osmosis in treating wastewater

Reverse osmosis (RO) membrane treatment system is frequently used in the desalination process and reclamation of reusable water. This is mainly due to the membranes being capable of eliminating up to 90–99% of pollutants in the water supply, such as total dissolved solids (TDSs) [47]. In this analysis, the four studies that perform LCA on the RO membrane treatment system use different types of wastewater and set in achieving different goals. This is reflected in the functional unit defined by these studies with an exception from [17] (Table 3).

**Table 3.** LCA studies on RO treatment system.

Reference	Goal	Source water	Functional unit	Software
[10]	RO membrane versus MCDI membrane	Textile wastewater	500 m <sup>3</sup> of wastewater per day	SimaPro
[17]	Reverse osmosis (RO)-nanofiltration (NF) versus NF-RO	Electroplating wastewater	Not defined	Gabi
[27]	Seawater desalination versus mine water reclamation using RO membranes	Seawater and mine water	1 kL of potable water produced at a specified standard over the life cycle of each process unit	SimaPro
[38]	Compare three scenarios of tertiary wastewater treatment	Industrial wastewater	1 m <sup>3</sup> of water for reuse as cooling tower make up	SimaPro

From the study by [38], three scenarios were set up to identify the environmental impacts that contributed the least to the environment. It is observed that adding an intermediate softening calcite seeding is the most environmentally favoured due to maximum recovery of RO. In treating textile wastewater, [10] found that the membrane capacitive deionisation (MCDI) performs better environmentally on all of the terms compared to the RO membrane. In making a comparison between treating seawater and mine water using RO membrane, both scenarios have the operational phase as the leading environmental impact. However, [27] identified that mine water reclamation has a better overall impact on the environment than seawater desalination. In making a comparison between the stages of RO and NF, [17] found that NF-RO had more impact on the environment than RO-NF with the highest from GWP. This is justified by the principle that RO membrane requires higher pressure than NF membrane and is more suitable to lower feed concentration. By making RO the second stage, more valuable energy would be consumed and less freshwater produced.

### 3.3 LCA of other membrane treatment system in treating wastewater

Table 4 shows that the remaining studies incorporated various membrane systems such as fuel cell technology [11], a wood-based filtration system with different membranes [14] and a hybrid treatment system [34]. Regardless, the source of wastewater being treated are mostly municipal wastewater [26] [15, 24] and wastewater [36, 11, 23]. However, there is no consistency between defining functional units despite having similar goals of different systems such as assessing between scenarios or methods.

**Table 4.** LCA studies on other membrane treatment systems.

Reference	Goal	Source water	Functional unit	Software
[7]	Evaluate shale gas extraction wastewater treatment	Shale wastewater	1 m <sup>3</sup> of treated water	Not defined
[11]	Assess fuel cell technology	Wastewater	1 L of treated wastewater	Gabi
[14]	Assess wood-based filtration system with different membranes	Industrial wastewater	30 × 30 × 5 mm <sup>3</sup> of Ginkgo biloba (Gb) membrane	Gabi
[16]	Assess two scenarios of electroless nickel plating treatment system	Electroless nickel plating wastewater	Environmental impact per m <sup>3</sup> of treated wastewater produced by the electroless nickel plating (ENP) industry	Gabi
[23]	Evaluate two different methods on wastewater treatment case	Wastewater	10 000 m <sup>3</sup> sewage per day	Not defined
[24]	Assess on polishing units in treated wastewater	Domestic/municipal wastewater	1 m <sup>3</sup> of delivered recycled water to be used for irrigation.	Gabi
[26]	Assess SPF process for secondary effluent treatment	Municipal wastewater	1000 m <sup>3</sup> of treated secondary effluent per day	Gabi
[30]	Evaluate community-based sewage water use	Sewage	Annual provision of space and water heating, irrigation and water treatment per person	OpenLCA
[34]	Hybrid system versus centralised water system	Greywater	1 m <sup>3</sup> water used for outdoor irrigation and/or toilet flushing	SimaPro
[36]	Locally produced AC versus conventional ACs	European wastewater	Amount of AC required to reduce FAE potential to a defined level in terms of comparative toxicity unit per 1000 m <sup>3</sup> of wastewater	OpenLCA
[37]	Assess three reclamation scenarios from petroleum refinery	Refinery wastewater	1 m <sup>3</sup> refinery wastewater from API/CPI separator	SimaPro
[43]	Assess desalination technology	Wastewater/seawater	1 L of treated water	Gabi

The studies by [7] and [43] focus on desalination of wastewater with differing desalination technology and functional units. From the study, [7] summarised that thermal-based desalination technology is the best method for desalinating water when compared to membrane distillation as it has a higher environmental impact when in comparison. However, [43] evaluated between microbial desalination cells (MDC), microbial fuel cells (MFC) and conventional treatment method to desalinate water and found that MDC has the highest environmental impact from the manufacturing and operation phase which contributes to the GWP of its whole life cycle. This is caused by the electricity consumption used to pump water for the MDC from its operation phase.

In treating municipal wastewater, [24] utilises different combination of microfiltration, ultrafiltration (UF) and ultraviolet (UV). UV treatment is deemed as the most environmental-friendly with cartridge filter and UF combination impacting the most for all impact categories evaluated [24]. [26] on the other hand uses solar photo-Fenton (SPF) and nanofiltration and identified the major environmental hotspots being electricity and chemical consumption for this type of treatment.

Studies by [16, 23, 37] were defined by assessing scenarios for wastewater reclamation with various sources of wastewater, software used and functional units. The proposed alternative scenarios from [16] proved to fare better in terms of climate change than the existing chemical treatment process for electroless nickel plating wastewater. The scenarios proposed by the study from [37] also displayed favourable results concerning the marine ecotoxicity and aquatic eutrophication impact which was reduced up to 90% and 84%, respectively. Assessing the LCA of a proposed scenario is a good way to assess the sustainability of a given system and aids in deciding which scenario provides the least environmental impact.

#### 4. Conclusions

It can be concluded that the LCA approach is increasingly being used as a decision support tool in sustainable water management, providing valuable insights on the environmental impacts of existing membrane treatment systems and in making improvements for future novel treatment processes. With various types of software and methodology available to conduct LCA, adapting it to a specific process or product in a given system is made easier. This is especially helpful considering wastewater treatment has a variety of treatment systems depending on the types of wastewater being treated.

However, with the broad application and set up of LCA within the membrane technology itself, making a comprehensive comparison between systems poses a challenge. Some of the challenges include the inconsistencies in specifying the impact assessment and methodology used for some journals and the lack of LCA study in certain regional areas. Hence, it is suggested that a more uniform implementation of LCA should be considered to ensure the reliability and reproducibility of results to allow a better implementation on novel or existing membrane systems.

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