Chapter 2
LCA for Membrane Processes

António A. Martins, Nídia S. Caetano and Teresa M. Mata

Abstract This chapter presents an overview of the current state of the art concerning the application of life cycle assessment (LCA) to assess and improve the environmental performance and sustainability of processes that use or are based on membrane technologies. A presentation of the LCA methodology is made, based on the current framework defined by the ISO Standard, focusing on the main aspects and how LCA can be applied to a given product or process system. A review of the available studies was done for membrane based or systems in which membranes have an important role, focusing in water treatment process, either for human and industrial application or wastewater treatment. The analysis shows that the application of LCA is still limited in membrane process, and more work still needs to be done, for example, taking into account the manufacture and final disposal/recycling of the membranes and their corresponding process modules, and to properly asses how membranes may increase the sustainability of existing processes by replacing existing technologies with larger environmental impact. As the need to evaluate the environmental impact and sustainability of new processes increases, the application of the LCA methodology will become more common both in process design and/or process operation.

Keywords Membrane technologies · Life cycle assessment · Sustainability evaluation · Environmental impact · Water and wastewater treatment

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A. Figoli and A. Criscuoli (eds.), *Sustainable Membrane Technology for Water and Wastewater Treatment*, Green Chemistry and Sustainable Technology,
DOI 10.1007/978-981-10-5623-9_2

2.1 Introduction

It is increasingly consensual that human development, coupled with the current patterns of production and human consumption, has resulted in significant environmental impacts. They can be of a local nature, for example, water and air pollution, or global, for example, global warming mainly due to burning of fossil fuels for energy generation. Recognizing that a course of change is needed at all levels, national, regional and city level, international organizations and governments have proposed and are implementing strategies to tackle the challenges of a more sustainable development [1–3].

Although the problems are global, the answer strongly depends on the context, in particular, on the local conditions and the stakeholders involved. For instance, industry tries to be increasingly more environmentally friendly and to fulfil its regulatory and legislative obligations without reducing its market competitiveness. On the other hand, citizens in general are better informed about the environmental issues, and demand an improvement of the environmental quality without compromising significantly their quality of life. Therefore, new or improved production processes are needed to supply the products and services needed for a progressively more globalized and developed world.

While the questions of production and consumption must be considered simultaneously, in this chapter the focus is on production systems. Currently, this is a key research area in the sustainability area that combines the expertise of many scientific disciplines, including engineering, economy and the social sciences.

More sustainable production systems, or at least with lower environmental impacts, require the retrofitting of existing processes or the development of new ones. Possibilities involve the utilization of renewable raw materials and/or energy instead of non-renewable, or the utilization of new technologies. Among them, membrane technologies are one of the best possibilities, currently seen as having great potential for improving the sustainability of current production systems. In some industrial activities membranes are already extensively used, as for example in water purification. Their utilization is increasing and new applications are being considered and developed for a wide variety of applications [4].

Membrane processes are a class of separation processes used to remove selectively components from a solution or suspension. The separation involves the permeation of a fluid through the membrane, in which certain components, either chemical compounds and/or solid materials, are retained. The product stream enriched with the components that cross the membrane is called permeate. The other stream is called retentate. Key factors influencing the separation are the components size (even for chemical compounds), the membrane characteristics (for example its porosity, pore size distribution, electrical charge, among others) and the magnitude of the driving force. A more detailed description about applications, operational and physico-chemical characteristics of membrane systems is beyond the scope of this work that focuses on their environmental performance, but it can be found in the literature [5–8].

When compared with other separation processes that fulfil the same tasks, membranes have some advantages, being some of the most relevant listed below [9].

- They normally operate at low temperatures and/or pressures, thus reducing the energy consumption. This is a relevant issue in process dealing with temperature sensitive raw materials and/or products, for example, food processing.
- Membrane characteristics can be fine-tuned to address specific separation requirements.
- Membrane can be made from a wide variety of materials, allowing the development of robust processes adapted to the process conditions and/or components involved [10].
- Membrane processes do not require the use of solvents.
- Membrane units can be made in a compact form, reducing the space needed to their installation and operation.
- Replacement of membrane units and/or parts can be done easily and fast, as they are built in a modular fashion.
- Simpler scale-up, by just adding or removing membrane modules/units, according to the processing needs.
- Although currently in most of the membrane processes the separation is purely physical, it is possible to functionalize the membrane, allowing, for example, the coupling of chemical reaction with separation. This is a form of process intensification, resulting in more efficient and compact processes. Currently this is a very active area of research, in which significant progress is expected in the near future [11–13].

Notwithstanding the advantages, the application of membranes in practice poses some challenges, and may have some environmental impacts that must be accounted for. Some of the most relevant include:

- Fouling that reduces the membrane capacity to perform the desired separation. Possible reasons include the accumulation of the contaminant in the interface between the fluid and the membrane, increasing the resistance to mass transfer. Other possibility is membrane degradation that may lead to membrane replacement.
- Membrane cleaning may be difficult or even impossible.
- Retentate or permeate disposal, depending if it is intended to remove or concentrate a certain component.

Thus, membrane processes and/or membrane unit operations are currently seen as more environmentally friendly options to perform a wide range of tasks, for instance, water processing, for either human/industrial consumption or wastewater

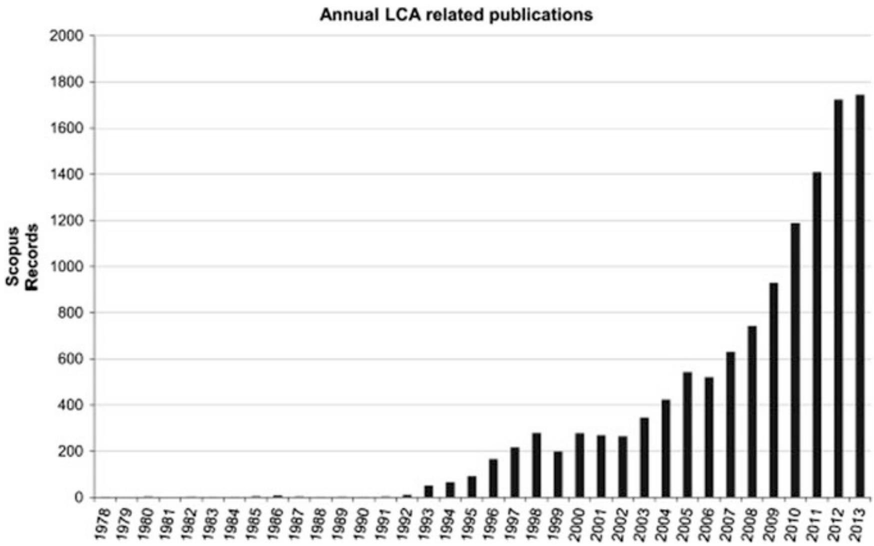

Fig. 2.1 Number of LCA related publications per area. Reprinted with the permission from Ref. [22]. Copyright 2015 Elsevier

treatment (WWT), food processing, fuel cell operation, among many others. They are even considered in some processes as the best available technology (BAT), for example, in the production of chlorine using electrochemical processes [14]. Many examples of studies and/or applications of membranes that claim to be more sustainable or contribute to sustainable development can be found in the literature [9, 15–20]. However, when designing and/or retrofitting a process in which membranes are a key part of the system, one needs to have objective environmental evaluation tools, for example, to identify which are the best options to use membranes and how they can improve existing processes. Of the various possibilities, life cycle assessment (LCA) has emerged in the last decades as the one of the relevant framework to assess the environmental impact of a product/service or a process [21, 22]. Figure 2.1 presents the evolution of the total number of LCA-related publications from 1978 to 2013 [22]. The figure shows an increase, in particular in the last decade, demonstrating that LCA is becoming a very relevant tool to evaluate the environmental impact of products and processes, with applications in a wide range of areas, even including legislation and/or regulations [22, 23].

In the next session, a brief description of the LCA methodology is given, highlighting the key aspects of the methodology, how it can be applied in practice, and extensions of the standard methodology.

2.2 Life Cycle Assessment (LCA)

LCA is a systemic methodology with the main goal of quantifying the potential environmental impacts of a product/service or process through its life cycle stages [24, 25]. LCA allows a complete analysis of a given product or process system taking into account all the life cycles associated with it, from extraction of raw materials to final disposal, making it possible to identify the steps with larger environmental impact in which improvements are needed. Although variations are possible, usually a LCA study includes the following steps: extraction and preparation of raw materials, manufacture, distribution, use, repair/upgrade/maintenance, and final disposal or recycling. This corresponds to the most general case, a cradle-to-grave analysis. Depending on the goals of the study and availability of data and/or impact assessment methodologies, it is possible to define other system boundaries for the LCA studies, for example, cradle-to-gate studies that do not consider distribution and consumption of products.

Accounts of the evolution of LCA in the last four decades can be found in the literature [22, 23], showing that the interest and application of LCA is growing, as shown in Fig. 2.1. Historically, LCA started between late 1960s and beginning 1970s to address the environmental impact of packaging systems, in particular for beverages [22]. Starting in the 1990s, there was an effort from some governmental and international organizations to define guidelines or even standardize how the LCA studies are done, allowing, for example, an objective and unbiased comparison of studies made by different organizations. These efforts resulted in a set of ISO standards, part of the ISO 14000 environmental management standards: ISO 14040:2006 [26] and ISO 14044:2006 [27].

2.2.1 Methodology Description

In this section, the key aspects of the LCA methodology will be briefly described. A full and in-depth description of the LCA methodology and its foundations is outside the scope of this chapter. Detailed descriptions of the LCA methodology and how it is applied in practice can be found in the literature [28–30].

The fundamental goals of an LCA study are as follows:

- Make a compilation of all relevant material and energy inputs and environmental emissions;
- Quantify the potential environmental impacts resulting from the system inputs and outputs;
- To interpret the results and to identify hotspots in the process, support decision-making, among others possibilities.

To fulfil these goals, the LCA standard ISO 14040:2006 defined four steps (Fig. 2.2): (1) Goal and scope definition, (2) Inventory analysis, (3) Impact

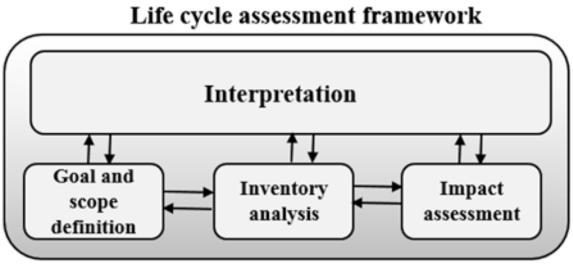

Fig. 2.2 LCA main steps, according to ISO 14040:2006

assessment and (4) Interpretation. The three steps in bottom line of Fig. 2.2 are normally performed sequentially, from left to right, as they depend on each other. Although the interpretation step deals mainly with the analysis of the impact assessment results, during a LCA study it is normal to critically assess the assumptions made in each step, the data quality and other relevant issues throughout the study.

2.2.1.1 Goal and Scope Definition

In the goal and scope definition step, the study purpose is described and its main goals are defined [31]. Depending on the context and specific circumstances in which the study is made, different types of studies are possible depending on what are its main aims, such as:

- Determine which life cycle stages contribute the most to a product/service or product whole life cycle impact, for which a complete life cycle is required.
- Compare different products/services or processes but with similar purposes.
- Determine the environmental consequences of changes in the process, for example, changes in the raw materials used or by using other process units.
- Obtaining the Environmental Product Declaration (EPD) of a product, for which specific regulations may apply.

In order to be able to compare different products or production systems, a common form of comparison is needed. This is done by defining a functional unit (FU), defined as a measure of the system main function or performance [32]. The study results are expressed in terms of the FU, ensuring that objective comparisons can be made between different product/service or processes systems. The definition of a FU also reduces any potential dimension effects, for example, when a product can be produced using processes with significant capacity variations. When performing a comparative LCA study, it is often necessary to define a reference flow that corresponds to a quantification of the product flows, including parts, necessary for a given product/service or process system to have the same performance defined by the UF [33].

Other key issues considered in the first step include:

- Definition of which relevant environmental impacts will be evaluated in the study and which methodologies will be used for it. This ultimately depends on the study objectives and the nature of the process. Guidelines for the definition of the adequate impact categories for a given study are available [33–35].
- Definition of the system boundary. As many products/services or processes involve many parts usually strongly interconnected, a selection of the most relevant must be done. This procedure ultimately depends on the assessment goals and the criteria defined.
- Assumptions concerning the study timeframe, types of process units, geographical settings, data sources, among others, strongly depend on the nature of the product/service or process considered.

The system definition and study timeframe must take into account if the study is dealing with a product/service or with a process. In the first case, that corresponds to most LCA studies performed and available in the literature, the various life cycle stages maybe be classified according to their position in the supply/production chain: extraction of raw materials, processing, distribution, consumption/usage and final disposal/recycling. An LCA study may be classified according to the life cycle stages considered, cradle to grave (full LCA) if all the previous steps are considered, cradle to gate (e.g. when the use and disposal steps are not considered) and others. Between the various life cycle stages transportation of raw/processed materials or products parts may take place. The distance travelled and mode of transportation depends on nature of the materials involved, local resources availability, among other issues.

In the case of processes, the system parts can be classified as follows: design and development, process construction and implementation, process operation and final dismantling. The timeframe is also dependent on the nature and type of the process, but it is usually much larger when compared to product/service systems, normally more than 10 years.

2.2.1.2 Inventory Analysis

In the inventory analysis phase, an input–output accounting is done, as complete as possible, of the materials and energy consumption, corresponding to the inputs, and to the emissions and waste generated during the life cycle, corresponding to the outputs. It involves three sub-steps done sequentially, as shown in Fig. 2.3:

In the first sub–step, a process flowchart is built that includes all relevant system subparts, such as transportation steps, raw materials processing, among others. Then, the inputs and outputs are identified, corresponding them to the fluxes of materials, waste and energy through the system boundary. The interrelations between the various system parts, in particular fluxes of energy and materials, should be clearly defined. Although not required, a visual diagram should be drawn, as it helps in better identifying and highlighting the relevant aspects of a given system.

Fig. 2.3 Substeps of the inventory analysis

The next sub-step corresponds to data collection, essential to be able to evaluate the potential environmental impacts in an objective way. In this process, raw materials and energy consumptions, and emissions resulting from the system activities are accounted for. Primary data, obtained, for example, from the real process units or product utilization is preferred. When it is not available, secondary data from the literature and/or databases or even the results of process simulation may be used whenever necessary. Energy usage impacts should take into account the local/regional conditions through the utilization of an adequate energy mix. In the last sub–step, each input and output, either of materials or energy, is expressed as a function of FU. The calculations may involve conversion of units and even solving material and/or energy balances whenever necessary.

The previous sequence is general but in practice it must be applied with caution. Problems in the inventory may arise when a company or production system produces a wide variety of products, or when process units are used and/or shared by different production systems and only the overall values of energy and materials are available. In these situations, it is necessary to perform an allocation procedure that consists in accounting only the inputs and outputs that correspond to a given product or service. Depending on the system and production process, several possibilities are possible, for example, allocation by mass, by value or by system expansion as recommended by the ISO LCA standard [28, 30, 36]. In some cases it may not be easy to define objectives and consensual allocation procedures are adequate for a given product/service or processes.

Other potential problem concerns data adequacy and quality, in particular, when secondary data from life cycle databases or the literature is used. Although in many cases, they are representative of real processes, when the technologies used and/or the local conditions are significantly different, the data may not be representative of the product/service or process system under study. In this situation, an effort to obtain primary data should be done, or a complete sensitivity analysis should be done, valuable to identify which aspects and/or emissions are more to the overall environmental impact. Also relevant, especially in systems with many input and output streams, is which consumptions and emissions should be considered. In practice, it is usual to define a cut-off value or percentage, bellow which the consumptions or emissions are not accounted. However, this procedure should be done with care, as the environmental impacts of different compounds are different and some significant consumptions and/or emissions may be not considered at all.

The organized input–output data is called the life cycle inventory (LCI), and includes a detailed description of all the materials and energy consumptions (corresponding to the system inputs) and emissions and waste streams generated (corresponding to the outputs) connected with a product/service or process life cycle. The data can be used to compare different processes or products/services directly, for example, energy consumption or emission of specific pollutants, a procedure in which expressing the inputs and outputs as a function of FU ensures an objective comparison. In this case, the study is called a life cycle inventory analysis (LCIA). However, usually the data and information gathered is used as a basis to evaluate the potential environmental impacts.

2.2.1.3 Impact Assessment

After creating the LCI, the potential environmental impacts can be determined, either for the overall life cycle or for the individual subparts of a system, depending on the specific goals of the study. According to current practice and the ISO Standard, four sub-steps can be defined, the first two are mandatory and the remaining two are optional, as shown in Fig. 2.4.

In the first sub-step, called classification, the various material and energy inputs and outputs are assigned to environmental impact categories previously defined in the goal and scope definition. Although there is some flexibility in the definition of impact categories, depending on the main environmental impacts associated to each product or process system [33, 34], the following set is commonly encountered: Global Warming Potential/Carbon Footprint, Ozone Depletion Potential, Eutrophication Potential, Photochemical Potential, and Acidification Potential. To each impact category corresponds an environmental indicator.

In the second sub-step, called characterization, each impact category is evaluated. The value of the corresponding environmental indicator is calculated using an impact assessment methodology, defined in the first step of the LCA methodology. One common approach involves the use of conversion factors, also known as characterization or equivalency factors, to convert the LCI results in values that can be compared between system parts or even other studies. Extensive lists of characterization factors can be found in the literature [37]. An example is the indicator Global Warming Potential/Carbon Footprint, which is calculated and expressed in

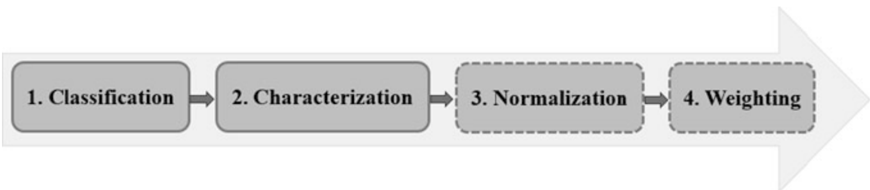

Fig. 2.4 Substeps of the impact assessment step

terms of mass of CO_2 eq. emitted to account for the different contributions to the greenhouse effect of different gases, for which emission factors were proposed by the IPCC [38].

When performing a LCA study or a process an interesting arises on how are the environmental impacts of the construction and/or dismantling phase evaluated and allocated to the functional unit. Those life cycle steps have a small duration when compared to the overall study timeframe, usually the process lifetime. If the UF is defined as a unit product, most of the times an objective measure of the system duration, it is normal to allocate the impact of the construction and dismantling to the total quantity of product produced, thus diluting in time the environmental impacts of those two life cycle steps.

The other two sub-steps are optional and can be done independently of each other. In the normalization sub-step, the impact assessment results are normalized using a reference factor. For example, they can be related to the environmental impacts of one product or specific life cycle stage. This procedure may clarify and simplify the interpretation of the results, highlighting, for example, differences not easily seen in non-normalized data.

The weighting sub-step is performed in some studies, especially when products or processes are compared with each other. It may not be easy to determine which product/service or process is better as no clear pattern can be extracted from the indicators values. Also, when presenting the LCA study results, in particular to non-specialists, the utilization of many indicators can be confusing and mislead the audience, a situation that may occur in decision-making processes based on LCA results.

Weighting tries to avoid these problems by combining all indicators in a single score/index. This process uses factors that reflect the relative importance of each environmental impact. Their definition is both a political and a scientific process, in which all relevant stakeholders play a part. Thus, no consensual weighting scheme exists. Hence, many practitioners do not apply weighting to the indicators. Although the report is more complex and may be ambiguous in some cases, there is no loss of information due to the weighting process.

2.2.1.4 Interpretation

The previous three steps follow a logical sequence. Albeit the interpretation step is the last one, from a practical point of view it occurs throughout the entire study, dealing with the questions of assumption assessment, clarification and adjustment, sensitivity analysis, and data and results checking. As the fourth and last step, current practice and the ISO standard consider two main goals:

- Analyse the results of the impact assessment in order to: reach conclusions, identify life cycle hotspots and/or which life cycle stages have the most significant environmental impacts, identify weakness/limitations, propose recommendations and/or improvements, find what are the main study conclusions, among others.

- Deliver a transparent and objective presentation of the LCA study, taking into account the goal and scope of the study.

A fundamental part of the interpretation phase is the analysis of the data used and how the calculations were performed, in particular, its completeness, reliability, sensitivity and consistency. In many LCA studies, a sensitivity analysis is performed in which various aspects are varied, such as assumptions, data sources, characterizations factors and data ranges. While this process makes a LCA study more complex, it provides extra insight on the results and supports the recommendations and decision-making process.

A critical review is also performed in many cases, for example, to fulfil regulation obligations in the issuance of environmental product declarations. It consists in the critical scrutiny by a third party, either a specialist or an independent organization of the LCA study. The main goals are to identify possible aspects that need to be improved, lend credibility to the LCA study, and avoiding potential bias resulting from the specific interests and background of practitioners and/or organization that commissioned the study.

2.2.2 *Extensions*

LCA, as defined in the ISO standards, only considers the potential environmental impacts of a product/service or process system to support, for example, decision-making and/or the implementation of measures to improve their environmental performance. While relevant, from a sustainability and even practical point or view, the results of an LCA study have a limited scope and potential, as the other key dimensions of sustainability are not taken into account, in particular, the societal and economic dimensions. Moreover, in practice LCA is used more often to assess products than process, as their life cycles are easier to define and it is easier to improve the overall system based on the study results.

2.2.2.1 Extended Methodologies/Frameworks

To allow the incorporation of other non-environmental related issues, some extensions of the LCA ISO Standard were proposed and are used, in practice, to complement the basic LCA framework. A comparison between the proposed extensions of the standard methodology is presented in Table 2.1, summarizing their aims/goals, main advantages and drawbacks.

The LCA methodology as defined in the ISO standards does not consider the time dimension, as life cycle stages and process system are fixed in time. This corresponds to an attributional LCA approach, as the environmental impacts are determined and attributed to each life cycle stage. It allows practitioners and decision-makers to identify environmental hotspots that should be considered for

Table 2.1 Extensions of the ISO LCA standard

Extension	Goals	Methodology characteristics	Particular issues
Social LCA, S-LCA, guidelines from UNEP are available [41].	Assess potential social and sociological impacts of product/service or process life cycle	Data sources: statistical census and/or economic data: jobs creation, workers income, etc. Possible indicators: local jobs created, labour practices, percentage or local jobs	Methodology follows the standard LCA methodology. The impact categories should be related to specific stakeholder groups, such as workers, consumers, local community, society and other value chain actors. There are still significant issues that have to be dealt with before S-LCA is more used in practice. In particular, in many cases objective data is not available, and there is lack of reliable and consensual impact assessment methods [42]
Life cycle costing—LCC. A code of practice was proposed by SETAC [43]	Evaluates the economic impacts of the various life cycle stages of product/service or process	The analysis includes not just the costs of raw materials and energy, but also the environmental costs. Possible indicators: cost of emissions, cost of waste treatment, etc.	In classic economic analysis of products and/or processes environmental costs are considered as externalities and not accounted in the calculations. Although it is consensual that these externalities must be accounted for, the methods available today for their estimation are limited, lack in objectivity and are not consensual

(continued)

Table 2.1 (continued)

Extension	Goals	Methodology characteristics	Particular issues
Life cycle sustainability assessment—LSCA. Guidelines for LCSA were published by UNEP [44]	Assess the potential sustainability impacts of product/service or process life cycle	Framework combines LCA, S-LCA and LCC. All indicators and data sources relevant to the previous methodologies are valid in LSCA, but care must be taken to avoid unnecessary duplication of information and/or results	As each methodology takes into account each pillar of sustainability independently, after combining their results an overall view of the sustainability of a product/service or process is obtained revealing, for example, what are the main issues that should be considered first when making decisions about products or processes. Still not significantly used in practice, but it is consensual today that a proper sustainability assessment should be based on a life cycle perspective

improvements, but it is possible to determine what will be the future environmental impacts. Consequential LCA seeks to do that, in particular assess what are the consequences of decisions and/or changes in the system under study, for example, technology changes. Contrary to the attributional LCA, the economic consequences of the changes must be taken into account. This is an important limiting factor when performing a consequential LCA analysis, as predicting the impact of changes in future systems is always complex and requires taking many assumptions, reducing the objectivity of the calculations [39, 40].

LCA and its extensions are also a key part of frameworks based on life cycle thinking (LCT). This approach tries to reduce the environmental, social and economic impacts of current human activities taking into account all the life cycle steps associated with them. This way it is possible to avoid burden shifting, and the solutions developed are closer to the optimal and reduce the overall impacts of producing, using and disposing of a product/service or process. The methodologies described before: LCA, S-LCA, LCC and LCSA, are the tools used in the LCT approach, supplying the information required for a proper decision-making.

LCT assesses the entire supply chain of a product, either upstream or downstream, and the environmental, social and economic impacts. Both qualitative and quantitative approaches can be used although the former is preferred from a management point of view. This way, LCT can help identify opportunities for improvement and support decision-making in all dimensions of sustainability.

LCT is starting to be at the core of strategies development, as it is a good way of taking into account all relevant aspects, including resources and energy consumption, stakeholders' needs and expectations, biodiversity protection, among others. Examples of practices and/or policies in which LCT plays a decisive role include: waste management, reduction of the energy consumption during the product use phase through an adequate product design, Green Public Procurement (GPP), definition of the best available technologies (BAT) for a production processes, among others [45–47].

2.2.2.2 Process Design

Although the ISO standards are easier to apply to existing product/service or process systems, they can also be applied to process design or to retrofitting of existing process, to improve their overall environmental performance. The application of LCA should start at the design stage, to ensure that the most adequate solutions are chosen. In addition, the cost of process changes is smaller in the beginning of the process design than later, in the process implementation or testing/start of operation stages [48]. As expected, the lack of data may be a significant problem, as the uncertainty in the process conditions and behaviour is large. Data from process simulations, laboratory experiments, life cycle inventory databases, scenario analysis and industrial practice can reduce the uncertainty and facilitate decision-making [48–51].

Despite the potential difficulties, it is widely recognized that LCA is a valuable tool to process design and optimization. Good reviews can be found in literature dealing with the application of LCA to chemical processes [52–54]. Frameworks and methodologies to process design including LCT/LCA principles were proposed, in particular, to account for the environmental impacts and sustainability issues whenever possible [48, 55–58]. Examples of the application of LCA in the design of chemical processes or in design criteria can also be found in the literature [59–61].

2.3 Application of LCA to Membrane Processes

Currently, the methodology of choice to assess the environmental impact of products/services and processes, the LCA methodology has already been applied to membrane-based processes or processes in which membranes play a significant role. As membranes are used in a wide range of process in various sectors of activity, this work will focus its attention in water treatment processes, in particular, for human consumption or for wastewater processing. Membranes are extensively used in the both cases to perform key steps, for example, to remove contaminants or undesirable compounds, for example salt from sea water to obtain fresh water. Other applications, such as energy applications (fuel cells), compound extraction and/or purification, gas purification, among others are only briefly presented in this chapter, even though they are increasingly important in a variety of applications.

2.3.1 Water Treatment Systems

Water treatment systems are extremely relevant from a sustainability point of view, as they help fulfil goal 6, clean water and sanitation of the UN sustainable development goals [1]. Moreover, water is fundamental in agriculture and in industry, sectors essential to satisfy the basic needs of human societies. Membrane systems or processes are already having an important role fulfilling those goals. Their importance and range of applications are expected to increase in the future, as membranes are a good option from an economical and environmental point of view when compared to other technologies.

Different technologies and system structures are used to wastewater processing or water production for human or industrial consumption. To the authors' knowledge, most of the LCA studies available in the open literature only considered one of the two possibilities, justifying the separation of the available works in two subsections, one for water treatment for human or industrial consumption, and other for WWT either of urban or industrial origin.

2.3.1.1 Human and Industrial Consumption

When considering water production for human or industrial consumption, membranes are usually used to remove contaminants that may have significant health issues or result in important corrosion and production quality concerns. For example, water softening increases the lifetime of plumbing and other flow equipment by reducing the potential for the build up of limescale, and reverse osmosis membranes can be used in this process. For human consumption, membranes are currently the main technology used in the desalination of seawater, a process increasingly important to human development, especially in regions where water resources are scarce or fresh water too polluted to be practical and economic its purification. Even tough the environmental impact of water production ultimately depends on the process conditions, according to the LCA methodology, a detailed knowledge and description of the operational conditions is not necessary. Comprehensive reviews of the utilization of membranes in water production for human or industrial consumption, in particular for desalination, can be found in the literature [62, 63].

Figure 2.5 presents a general production system to obtain water for human consumption [64]. It incorporates all relevant processes and life cycle stages, in particular, water extraction and treatment, waste disposal, chemicals and energy

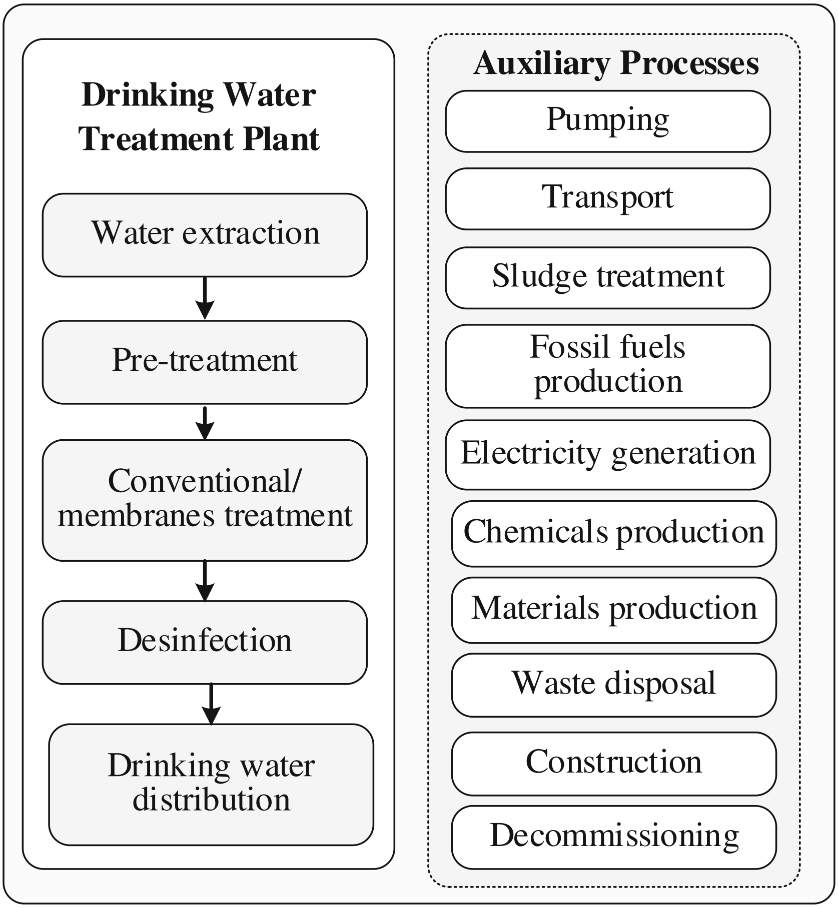

Fig. 2.5 General water production process for human or industrial consumption

production and utilization, and water distribution to the consumer. Depending on particular conditions or the final water application, some of the process units or processes presented in Fig. 2.5 may not be used. It can be seen that membranes are mainly used in the treatment stage to remove contaminants. In the case of seawater desalination that will correspond to salt removal. Membranes do not operate alone but combined with other upstream and downstream process units. Hence, when performing a LCA study of a water producing system for human consumption, membranes or membrane technologies are usually considered integrated in the process system.

Table 2.2 presents and compares the main features of some LCA studies performed for water production systems for human consumption that incorporate membrane processes and/or technologies. For each study, the following information is given: water source, FU, goal of the study, system boundaries and main life cycle

Table 2.2 Comparison of LCA studies for water production for human consumption

Source	Water Source, FU, Goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Raluy et al. [65, 66]	Water source: sea water. FU is the daily production of 45,500 m^3/day of potable water, with 8000 h of operation per year, for 20 years operation. Goal: reverse osmosis compared with thermal evaporator technology	A cradle-to-grave analysis of the desalination process was performed. Process construction, membrane replacement and materials consumption are considered primary data from existing plants was used whenever possible. Environmental impacts were evaluated using several methodologies: CML, Eco-Points 97 and Eco-Indicator, for various environmental indicators. Calculations were performed using SimaPro software	Results show that reverse osmosis has an environmental impact an order of magnitude lower than technologies based on thermal evaporation, The influence of the energy source, in particular. electricity was analysed, showing that utilization of renewable energy can significantly reduce the environmental impact
Hancock et al. [67]	Water sources: sea water and low salinity waste water. FU: 3875 m^3/day. Goal: comparison between standard process with a new one based on forward osmosis, combining seawater desalination with water reclamation	System considers only water processing, considering also the production of membranes and materials consumption. Water preprocessing and final distribution not considered. Primary data combined with databases was used. Ten environmental impact categories were used using CML methodology and SimaPro software to perform the calculations	Results show that module design and cleaning intensity are the keys to improve the environmental impact. New process has more impact, but it is shown that with proper optimization the same environmental impact of standard process is reached
Tarnacki et al. [68]	Water source: sea water. FU: 1 m^3 of treated water. Goal: compares two desalination processes: standard based on reverse osmosis and a new proprietary process	Several scenarios for localization and energy sources were analysed. A cradle-to-grave analysis was done, including construction and decommissioning, but without membrane production. Data from inventory databases was used. Impacts were assessed using Eco-Indicator, CML and Eco-points using GABI	Energy production is the dominant source of environmental impacts. Heat recovery and the utilization of renewable energy could be forms of reducing the overall environmental impact

(continued)

Table 2.2 (continued)

Source	Water Source, FU, Goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Friedrrich et al. [69]	Water Source: Groundwater. FU: 1 m^3 of potable water. Goal: compares standard water purification: standard based in flocculation and ozonification and membrane-based filtration, for the reality of South Africa	Cradle-to-gate study, including but without inclusion of membrane manufacture and disposal. Data was obtained from inventory databases. Seven impact categories were evaluated and compared for the process using CML methodology. Gabi software was used to perform the calculations	The study results show that it is not clear which water production process is better according to their environmental impact. The operational stage is responsible for most of the environmental impacts
Biswas [70]	Water source: seawater. FU: 1000 m^3 or potable water. Goal: analysis of a water desalination process in project in Western Australia, that includes microfiltration and reverse osmosis	Cradle-to-gate study in terms of water, not taking into account equipment production and process construction and decommission. Membrane production and replacement is taken into account. Primary data from constructor and suppliers was used. Only one indicator considered: Greenhouse emissions, expressed in terms of carbon equivalents. SimaPro software was used to perform the calculations	Results show that energy production and consumption is main factor controlling the emissions of greenhouse gases. The utilization of renewable can reduce emissions up to 90% when compared with base case study
Bonton et al. [71]	Water source: lake water with a high content of organic matters. FU: 1 m^3 or potable water. Goal: Comparison between of two water treatment plants: one conventional using activated carbon and the other based on nanofiltration	Cradle-to-gate study, taking into account the construction, operation and decommission process plant. Data from two water producing units in Quebex was used. Membrane life cycle considered only partially due to the lack of data. For environmental indicators were assessed using Impact 2002 + methodology. Calculations were performed using SimaPro software	Results show that the environmental impacts depend strongly on the energy source. The process involving nanofiltration is better than the conventional process. The consumption of chemicals is significant from and environmental impact point of view

(continued)

Table 2.2 (continued)

Source	Water Source, FU, Goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Stokes and Horvath [72]	Water source: river, seawater or recycled water. FU: 123,000 m^3. Goal: compare the environmental impact of producing potable water using three water sources	Cradle-to-grave study, taking into account the entire process, including the construction and decommission phases. Desalination process involves reverse osmosis. Data was obtained from two Californian treatment plants. Six environmental indicators were considered using a software tool, WEST, specifically designed for water treatment systems	Desalination process has the largest environmental impact, showing the importance of the water source when producing potable water. Better option is recycled water. Energy impacts and costs are the dominant factors in the treatment process
Holloway et al. [73]	Water source: used potable water. FU: 1 m^3 of reusable water. Goal: compares two process, one using a membrane bioreactor and the other a reverse osmosis based process	Cradle-to-gate study, taking into account also the construction and decommission phases. Processes were designed using rigorous process simulation and using data from industry and the literature. Energy consumption/carbon emissions were selected was environmental indicators. A specific tool designed to assess water Treatment systems, WWEST, was used	Results show that the operational phase has the largest energy consumption and environmental impact. It is shown also that process optimization can lead to significant reductions on the environmental impact
Jikakli et al. [74]	Water source: Brackish groundwater. FU: 1.25 m^3/d. Goal: Compare the performance of three desalination operating with solar renewable energy, one based on reverse osmosis	Cradle-to-gate study, but construction, decommission, and membrane production were not accounted for. Data was obtained from the EcoInvent inventory database. The Eco-Indicator 99 methodology was used to evaluate 11 environmental indicators. Calculations were made using SimaPro software	Results show that reverse osmosis has the lowest environmental impact. Energy and materials consumption are the most relevant aspects during the operational phase. The key inputs and emissions are identified for each life cycle stage

(continued)

Table 2.2 (continued)

Source	Water Source, FU, Goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Garfi et al. [75]	Water Source: several. FU: 1 m^3 of potable water. Goal: Compare several options for potable water production and distribution, including one based on reverse osmosis, for Barcelona (Spain) conditions	Cradle-to-gate study. Construction, decommission, and equipment construction and disposal not considered. Domestic and large scale production was considered for each technology, and data from existing water treatment plants was used. Six Environmental indicators were considered, using CML to evaluate the environmental impact. Calculations were performed in the SimaPro software	Results showed that the current traditional system is the best option. For the reverse osmosis small scale production leads to lower environmental impacts, yet large scale production has lower costs
Igos et al. [76]	Source water: river water. FU: 1 m^3 of potable water. Goal: Analyse and identify each are the main hotspots in terms of environmental impacts of existing potable water production systems	Cradle-to-grave study, including construction, equipment, and overall process infrastructure. Data was obtained as much as possible from two French units. ReCiPe and Impact 2002+ were used to evaluate the environmental impact, and calculations were performed SimaPro software	Results show that infrastructure has small environmental impact, mainly resulting from solid deposition and water distribution.. Main impacts are due to energy consumption, for process operation or for activated carbon production
Raluy et al. [77]	Source water: seawater and river water. FU: 25,000 hm^3 (total water transferred). Goal: compare the environmental impact of potable water supply by water desalination, using reverse osmosis, or river water transfer	Results from a previous study on the environmental impact of water desalination technologies [65] by the same authors were used. Three impact assessment methodologies were used: CML, Eco-points, and Eco-Indicator, using SimaPro software to o the calculations. Both primary and secondary data was used	Results support the conclusion that water transfer is the option with lower environmental impact. The operational phase is the dominant life cycle stage, in particular due to energy consumption

(continued)

Table 2.2 (continued)

Source	Water Source, FU, Goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Vince et al. [78]	Source water: Various sources. FU: 1 m^3 of potable water. Goal: compare the environmental impact of different scenarios for potable water supply, to support the development of decision supporting tool	Cradle-to-grave study, taking into accounting construction, equipment and process infrastructure, but not decommission. Inventory data was obtained from LCI databases. Eight indicators were evaluated using the Impact 2002+ methodology. Calculations and tool development was done using Gabi software	A general analysis of water producing systems concluded that energy generation and consumption has the largest environmental impacts, followed by materials consumption
Ras and Blottnitz [79]	Source water: raw water with known composition. FU: 1000 m^3 of boiler feed water quality. Goal: compare reverse osmosis and ion exchange to reduce water hardness and salinity	Cradle-to-grave study, not considering construction, decommission and equipment. Process data was combined with information from LCI databases. Six environmental indicators were considered using the CML methodology to evaluate the environmental impact. Calculations were performed using SimaPro	Results show that the membrane process option has higher carbon emissions, due to the larger energy consumption, but the remaining environmental impacts are lower. Moreover reverse osmosis generates lower salt waste quantities for disposal
Ribera et al. [80]	Source water: river and groundwater. FU: 1 m^3 of potable water produced. Goal: evaluate the change in environmental impact of implementing nanofiltration in an existing Spanish water treatment plant	Cradle-to-gate study, including construction and equipment, but without decommissioning. Data from real water treatment plants was used, complemented with inventory databases. Twelve environmental indicators were evaluated using the ReCiPe methodology. Calculations were performed using the SimaPro software. S	Several scenarios were studied regarding production capacity and membranes. Results show that increasing water quality also increases the overall environmental impact. A decision supporting tool was developed based on the results

stages considered, membrane processes or technologies considered, data sources, impact evaluation methodologies used, software used if any and main conclusions of the study.

Although the set of selected studies do not represent a full review of the area, they are nonetheless representative of the current state of the art in the area. A comparative analysis of the various studies presented in Table 2.2 allows some conclusions to be drawn. Most of the studies are recent, less than 15 years old, revealing that there is an increasing recognition of LCA as a valuable tool to assess the environmental impact of water production processes [22]. The majority of the works compares different types of technologies, including membranes, with the goal of determining which process or processes have lower environmental impact. Moreover, most of the works presented in Table 2.2 deals with the production of water for human consumption, in particular, desalination processes. For industrial utilization, the application of LCA is much more uncommon. An attributional approach is preferentially used, as the main goal of the LCA studies is to compare the environmental impact a certain quantity of water with a given quality.

Concerning the selected FU, all of the studies considered a certain amount of water produced with wide variations between the values. Also, the source of water can vary significantly between studies, complicating the comparability between studies. While some variation exists in the definition of the system boundaries, the majority of the studies consider the construction of the process units and production systems, and the various production steps from water extraction to water processing, in a cradle-to-gate perspective. However, the production and final disposal of the membranes is seldom taken into account. The water distribution to the final consumer is also rarely considered. As much as possible, data from primary sources is used. The use of LCA software is common to perform the inventory and impact evaluation calculations. Some variability is observed in the selected environmental impacts and methodologies used to evaluate them, making it difficult to compare the results of different studies. The results show that membranes in most situations have better performance in terms of environmental impact when compared with other processes. The impacts due to energy consumption and utilization are the most relevant factors controlling the process environmental impact.

Barjoveanu et al. [81] also performed a comprehensive review of the application of LCA for water treatment systems for human consumption. The authors concluded that most studies consider full treatment systems and compare different technologies, in which membrane systems are a common choice, focusing in particular in the environmental impacts of energy consumption. The study highlights the need to define new impact categories for the economic impacts, and more accurate data. For desalination processes, Gude [82] and Zhou et al. [83] also give a good review of the current state of the art and future research and development trends, focusing on the sustainability of existing and future production. Zhou et al. [83] concluded that much work is still need in the life cycle inventory, in particular, the necessity of using primary data for a proper environmental impact assessment, and more adequate environmental assessment methodologies.

Most studies only considered the LCA methodology as defined by the ISO standards, without any extensions. Nevertheless, it is possible to find some studies that went beyond it. One example is the work of Stokes and Horvath [72] that combine LCA with input and output analysis to assess the costs of the various source water options. The authors concluded that the environmental costs are less than 10% of the overall process costs, and the best option is to use recycled water. Holloway et al. [73] used a consequential LCA approach to compare two options for water treatment, using computational tools to model the processing systems, to understand how the system can be optimized in terms of environmental impact.

Several studies considered process intensification in water treatment for human consumption, for example, combining membrane separation with chemical reaction. Manda et al. [84] studied the potential of using membranes for the removal of micro pollutants from drinking water, in particular, active compounds used in pharmaceutics. An enzyme-coated membrane was compared with a process based in activated carbon using a cradle-to-grave LCA study, considering the production and disposal of the membranes. The FU was 1 m^3 of purified water, data was obtained from the literature and LCI databases, and the environmental impacts were evaluated using the ReCiPe methodology using SimaPro software. The results show that the membrane process is better from an environmental point of view depending on the source of energy and how it is operated, in particular, the frequency in which the membrane is recoated with enzyme.

Lawler et al. [85, 86] examined the life cycle of reverse osmosis membranes used in water desalination processes, including the production and end-of-life options available, a growing problem due to increased production of drinking water from seawater. The authors reviewed the various disposal and regulations applicable, and developed a life cycle model to assess and compare the environmental impact of several end-of-life options. The authors considered as FU a standard membrane module, adequate in this case as their goal is to assess the environmental performance of membranes. Membrane production and disposal was considered and primary data for Australian conditions was used as much as possible. The results show that the characteristics of the membranes have a minimal impact in the environmental impact, and that membrane reuse is better than landfill deposition. The results also show that incineration is also preferable to landfill disposal, even with higher carbon emissions for incineration, but the distance involved should be taken into account in the decision. The study also provides guidelines to help manufacturers and users of reverse osmosis membranes in deciding about the most adequate end-of-life options.

The LCA methodology was also incorporated in modelling and/or optimization tools developed to assist in the design and/or operation of processes for the production of potable water. An example is the work of Vince et al. [78, 87] that looked at the optimization of reverse osmosis based process plants for the production of potable water, combining both economic and environmental aspects. Two environmental indicators were selected, the total recovery rate and the electricity consumption, as they are related to process efficiency and are a measure of the energy consumption, being the last the aspect most relevant for the overall process environmental impact. A FU of 1 m^3 of drinkable was selected and data was obtained from inventory databases. The study concludes that it is possible to design a process that takes into account the trade-offs between costs and environmental impacts, but it is strongly dependent on the local conditions, in particular, availability of renewable power sources.

Mery et al. [88] developed a LCA-based computational tool, EVALEAU, to design and assess the environmental impact of water treatment processes for human consumption. The Umberto LCA software was coupled with a library in which the more relevant processes involved in water treatment systems are described and rigorously modelled. Process data and information from the EcoInvent database were combined to provide a better description of the process consumptions and emissions. A sensitivity toolbox was also implemented to identify process hotspots that represent opportunities for improvement. The tool was applied to a real case study of a water treatment plant in the Paris region, France, and good agreement was observed between simulated values and real data. Ahmadi and Tiruta-Barna [89] included an optimization module in EVALEAU, as a way to tackle the trade-offs between LCA and the economic analysis. The improved tool was used to the case study considered by Mery et al. [88], considering the minimization of environmental impacts (determined using the ReCiPe methodology) and costs and the maximization of water quality.

Loubet et al. [90, 91] developed a tool, WaLA (water system life cycle assessment), to assist in the LCA analysis of urban supply systems. A modular approach was considered, in which each module is a description of a technology (including membrane processes) or process step and/or operation. The tool was implemented in MATLAB/Simulink. The data needed to operate the tool is obtained from the literature, databases or is user input. The WaLA tool was applied to a case study dealing with the water supply in suburban Paris, France. Several future scenarios were compared and the results show that WWT plants have larger environmental impacts when compared to drinking water production and distribution, and the impacts of climate change can be significant in the future.

Beery and Repke [92] analysed the sustainability of various seawater pretreatment methods for reverse osmosis. Both LCA and LCC were used, combined with some selected social factors. A FU of 1 m^3 of potable water produced for a source water with the following characteristics: TDS of 35,000 ppm, temperature of 25 °C. pH equals to 8. The results show that membrane pretreatment is preferable from an economic point view, but less attractive in the environmental and social dimensions. This is due to the higher energy consumption and less flexibility in defining the process characteristics. The authors concluded that more research is needed to improve membrane performance and reduce the environmental impact.

2.3.1.2 Wastewater Treatment

Figure 2.6 presents a generic process system for WWT [93]. It incorporates all the main life cycle stages, in particular, the various types of treatment aimed to deal with specific contaminants. For instance, the biological treatment serves to remove

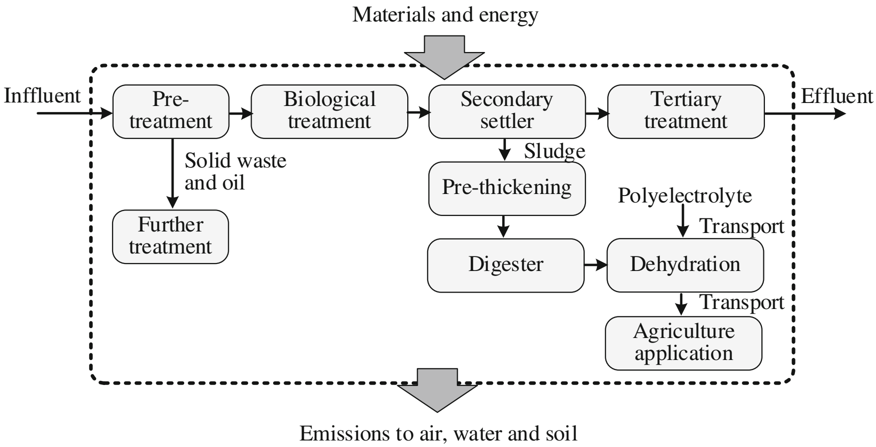

Fig. 2.6 General wastewater treatment process

organic contaminants from wastewater, and in the pretreatment step solids entrained with the wastewater may be removed by filtration. Membrane processes or technologies can be used in the various stages of WWT. When compared to conventional processes, membranes units are more compact, they can achieve higher purification efficiencies, and even in some cases allow the removal of valuable components thus improving the overall process economics [94]. An interesting example is the membrane biological reactors (MBR) that combined membranes with biological treatment, avoiding the need for a downstream filtration to remove biological particles and living cells [95]. The increasingly demanding requirements placed in WWT and the need to recycle and/or reuse water are increasing the attractiveness of membranes processes in WWT. A full description of how membranes can be applied to WWT is outside the scope of this work and can be found elsewhere [94, 96].

As in the case of water production for human or industrial consumption, membranes are used coupled with other process units. Thus from a LCA perspective they have to be considered integrated in the process system. Table 2.3 presents and compares the main features of some LCA studies performed for WWT systems that integrate membrane processes and/or technologies. For each work information is given on the characteristics of the wastewater, FU, goals of the study, system boundaries and life cycle stages considered, membrane processes or technologies considered, data sources, impact evaluation methodologies used, software used if any, and main conclusions of the study.

As in Table 2.2, the set of studies listed in Table 2.3 does not present all available studies in which LCA was applied to the WWT systems that include membrane systems. Nevertheless, the sample of studies can be considered representative, and some conclusions about the current state of the art and potential aspects to be improved can be made. Similar to the situation observed in water

Table 2.3 Comparison of LCA studies for wastewater treatment consumption

Source	Water source, FU, goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Memon et al. [97]	Source water: greywater of urban households. FU: Variable dependent on water consumption and greywater generation Goal: compares four different treatment processes, including a biological and chemical membrane reactor	Construction and process operation are considered, assuming for design purposes that system will serve 500 households. Energy and materials consumption are accounted for. Data was obtained from suppliers and simulation results. Ten environmental impact categories were considered, using CML and Eco-Indicator as evaluation methodologies. Calculations were performed using SimaPro software	Processes based on natural processes have the lowest environmental impacts. Amid membranes is the chemical membrane which has the worst performance. Utilization step is dominant for all technologies. A tool for greywater treatment process selection was developed
Ortiz et al. [98]	Source water: urban wastewater from a small Spanish city with a population of 13,200. FU: 3000 m^3/day or treated water. Goal: Compare three process variants: without membranes, with ultra filtration, or with a MBR	Construction, membrane replacement each seven years, and process operation are taken into account. Data was obtained from an existing wastewater treatment from a small Spanish town. Five environmental impact categories were considered, using CML 2 baseline 2000, Eco-Points 97 and Eco-Indicator 99—as assessment methods. Calculations were performed in SimaPro software	Results show that the process operation has the largest environmental impact. The inclusion of the membrane process increases the environmental impact when compared with conventional process, but better final water quality justify their inclusion

(continued)

Table 2.3 (continued)

Source	Water source, FU, goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Coday et al. [99]	Source water: wastewater resulting from shale oil extraction. FU: 1 barrel of wastewater generated. Goal: compare two forward osmosis treatment process for water recover: standalone or a complete osmotic dilution system; with transportation and well injection for water disposal	Cradle-to-gate study, including construction and equipment, for the membrane-based processes, and gate to gate for transportation and well disposal. Data was obtained from the literature and from the USA Input-Output 2002 database. Calculations were performed in the SimaPro LCA software, for ten environmental impact categories, and using TRACI as evaluation methodology	Energy demand is main contributor in the membrane-based processes for the overall environmental impact. Results show that the environmental impacts of the three processes are similar, but membranes can reduce significantly pit water management costs and the need of wastewater transportation
Remy and Jekel [100]	Source water: wastewater from a small town of 5000. FU: not specified but takes into account human needs. Goal: energy analysis of various processes, including a MBR	Cradle-to-gate study, considering construction of infrastructure but not equipment. Data was based on information from a real wastewater process in Germany, coupled from information from databases for the materials used. The cumulative energy demand was the one indicator evaluated. Calculations were performed using Umberto software	Process operation and materials require similar amounts of energy. Anaerobic digestion only reduces slightly the energy needs. System involving the MBR has the worst performance in terms of energy consumption
Remy et al. [101]	Source water: wastewater with a COD of 120. FU: defined as population equivalent per year, for a total of 87.6 million m^3/year. Goal: compare several technologies for	Cradle-to-gate study, including construction and operation. Ultrafiltration and filtration with a ceramic membrane were considered. Data was obtained from a real life wastewater	Results show that water quality in processes involving membranes is higher, but with larger energy and materials consumption. Non membrane processes are able to fulfil

(continued)

Table 2.3 (continued)

Source	Water source, FU, goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
	tertiary water treatment in a wastewater treatment plant in Berlin	plant and inventory databases. Energy cumulative consumption and six environmental indicators evaluated using the ReCiPe 2008 were selected. Calculations were performed using Umberto software	requirements, making membranes processes non competitive
Kobayashi et al. [102]	Source water: urban wastewater from an Australian city. FU: 18×10^6 m^3/year. Goal: compare the environmental impact and risk for the human health of recycling wastewater for human consumption, involving reverse osmosis	Work combines LCA and quantitative microbial risk assessment. Construction and final disposal, as well equipment, are not take into account. Primary data was complemented with data gathered in databases. Six indicators were considered using ReCiPe for their evaluation. Calculation were performed using Gabi 6 software	Energy consumption in the membrane process is the most relevant issue in terms of impact. Although recycling water increases impact, water quality is improved. Also, the usage of renewable energy reduces the overall environmental impact
O'Connor et al. [103]	Source water: pulp and paper industrial wastewater with high COD and organic halides. FU: 100 m^3 of recycled water for irrigation. Goal: compare four treatment alternatives, including reverse osmosis and ultrafiltration	Cradle-to-gate study, excluding decommissioning but including construction whenever data was available. Process calculation performed using Matlab using information from the literature. Four indicators were considered using CML as impact evaluation methodology. Calculations were performed using SimaPro	Energy consumption increases with treatment intensity. Yet, carbon emissions can be controlled through and adequate sludge disposal. Process configurations have the largest energy consumption

(continued)

Table 2.3 (continued)

Source	Water source, FU, goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Pintilie et al. [104]	Source water: urban wastewater from Tarragona, Spain. FU: 1 m^3 entering wastewater treatment plant. Goal: compare the impact of having or not tertiary water treatment, which includes a reverse osmosis process, in potential water reuse	Only operational activities were considered. Primary data is obtained from a real wastewater treatment plant, complemented with information from databases. Ten environmental impacts were assessed using ReCiPe methodology. Energy cumulative demand was assessed using the CML methodology. Calculations were performed in unspecified LCA software	Tertiary treatment increases the environmental impact, in particular due to the increase in energy consumption. Water quality improvement may be relevant depending on the local water resources, and utilization of renewable energy may reduce significantly environmental impacts
Pirani et al. [105]	Source water: wastewater generated in Masdar City, Abu Dhabi. FU: 1 m^3 of treated water. Goal: compare two technologies for wastewater treatment: a conventional activated sludge reactor and a MBR	Cradle to gate but without the construction and decommission of process units. Membrane construction was considered. Data from inventory databases and literature was used. The Eco-Indicator 99 was used to evaluate the environmental impacts. Calculations were done using the SimaPro software	MBR has lower environmental impacts when compared with the conventional activated sludge process. However, energy consumption is high. MBR is better used in a decentralized way
Vlasopoulos et al. [106]	Source water: wastewater originated in oil and/or gas extraction processes. FU: 10,000 m^3 of wastewater processed for 15 years. Goal: Compare several treatment technologies, with the goal of reusing	Cradle-to-grave study, considering construction of process system and units. An extensive analysis of the potential process combinations was done. Primary data from constructors and process units suppliers	For most technologies, including membranes, the environmental impacts result mainly from the operation phase, in particular due to the energy consumption. The results show that for this type of waste water

(continued)

Table 2.3 (continued)

Source	Water source, FU, goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
	treated water for agricultural purposes	was used as much as possible. Five environmental indicators were considered using the CML evaluation methodology. Calculation were done using SimaPro software	micro filtration is a good choice
Rahman et al. [107]	Source water: urban wastewater for average US conditions. FU: 1 m^3 of incoming wastewater. Goal: compare several advanced removal processes for nutrient removal, especially N and P, including membrane processes	Cradle-to-grave study, considering construction and process operation. Three levels of treatment are studied considering different treatment process configurations. Inventory data was obtained using process simulation combined with databases. Five environmental indicators were quantified using TRACI as evaluation methodology Calculations were performed in SimaPro software	Results show that more efficient technologies, including membranes, reduce the environmental impact, at the expense of larger energy and chemicals consumption. Inclusion of tertiary treatment may not be adequated due to the increase in the overall environmental impact
Høibye et al. [108]	Source water: wastewater generated under Danish conditions. FU: 1 m^3 of treated wastewater. Goal: compare FIVE treatment technologies, including a MBR, considering technical, economic and environmental aspects	Only process operation was considered in the process system. Data was obtained from the literature and inventory databases. Environmental impact assessment was performed considering several contaminants and four indicators, evaluated suing the EDIP methodology. No specific software was used in the calculations	The results show by using a MBR larger environmental impacts will result, due to larger energy consumption, but with an improved water quality. The best process depends ultimately on the desired water quality

(continued)

Table 2.3 (continued)

Source	Water source, FU, goal	System boundaries, membrane technologies and impact evaluation	Main study conclusions
Garcia-Montoya et al. [109]	Source water: wastewater with a COD of 900 g/m^3. FU = One person Equivalent per year. Goal: Compare several forms of water reuse, including wastewater treatment based on a membrane bioreactor, for a case study of the Mexican city of Morelia	Only the operational and maintenance activities are considered. Inventory data is obtained from Mexican wastewater treatment plants and from process simulators (Aspen-Hysis). Seven environmental indicators were evaluated using IMPAC 2002 + methodology. No specific software was used in the calculations	Results show that higher final water quality is obtained in the scenarios involving the membrane bioreactor, at the expense of higher energy consumption and overall environmental impact. The study shows that it is possible to fulfil fresh water needs while minimizing the environmental impact
Machado et al. [110]	Source water: wastewater with a COD of 900 g/m^3. FU = one person equivalent per year. Goal: compare three wastewater treatment processes aimed for small and decentralized communities, including one that use a geotextile membrane	Cradle-to-gate study, construction and maintenance was taken into account. Inventory data was obtained from the literature and inventory databases. Six environmental indicators, including energy consumption, were evaluated using the CML methodology. Calculations were performed in SimaPro software	Results show that systems design for low energy consumption, including the geotextile membrane, have lower energy and environmental impact. Several proposals to improve the environmental performance were proposed and evaluated

treatment systems for human/industrial consumption, most of studies are less than 15 years old, following the trend observed in the last two decades of the increase importance given to LCA as one of main tools to assess the environmental impact of systems, either products and processes [22]. Most works analyse complete WWT systems that include membranes processes performing specific tasks, usually in tertiary treatment. As in Table 2.2, the comparison between various technologies, among which membranes, in terms of environmental impact is one of the main goals of the studies. Wastewater of various origins and characteristics are considered in the studies, resulting in significant variations inter studies in the FU defined. Most of the studies take into account all water processing stages, construction of infrastructure and equipment, but the final disposal/distribution and membrane production are seldom considered. As much as possible primary data was used, in particular, from real operating WWT plants, complemented whenever necessary with data from LCI databases. The use of LCA software is common, both to perform and/or complement the data inventory and to carry out the assessment of the environmental impacts. Significant variability is observed in the environmental impacts quantified and the methodologies used to assess them, even though energy consumption and greenhouse gases emissions are normally considered. Combined with the variability in the FU and wastewater sources, this situation makes the comparison between studies complex if not impossible. The results show that the utilization of membranes normally results in better processed water quality, but at the expense of larger energy and chemicals consumption. The impacts due to energy consumption and utilization are the most relevant factors controlling the process environmental impact

Barjoveanu et al. [81] and Coriminas et al. [111] also reviewed the state of the art concerning the application of LCA to WWT systems. The authors concluded that it is clear that LCA is a valuable tool to improve the environmental performance of WWT systems, and practitioners are increasingly aware and interested in the methodology. The analysis of the literature also shows that there is some variability between studies, in particular in definition of the FU, system boundary, impact categories and calculation methods. A need to develop standard guidelines to apply LCA in WWT is identified, to ensure the quality, reproducibility and comparability of studies in the area.

Most of the studies presented in Table 2.3 used on the standard methodology, as described in the ISO standard. To the author's knowledge, no works exist in the open literature in the consequential LCA framework or S-LCA was applied to WWT systems involving membrane processes or technologies. Concerning LCC, Life Cycle Costing, some examples can be found in which the methodology was used coupled with LCA. Coday et al. [99] have applied LCC in their cases study, taking into account the costs of all the treatment stages of both technologies. The authors concluded that the forward osmosis treatment is significantly cheaper than the standard procedure of deep well disposal. Garcia-Montoya [109] consider the operational costs in their analysis of WWT for residential consumption, having demonstrated that it is possible to simultaneously optimize the overall environmental impact and the costs of running such systems.

Table 2.3 only lists studies in which full WWT systems that integrate membrane technologies are considered. From a practical point of view, this approach allows the comparison of different treatment, but does not allow a detailed analysis of the membrane systems and has their performance depends on the other parts. Yet, it is possible to found in the literature LCA studies in which the study scope is the membrane process alone not coupled with other processes. An example is the work of Hospido et al. [112] that compared four types of membrane reactors used for WWT with different configurations and complexities. The production of the membrane units was taken into account. A FU of 1 m^3 of permeated produced was used, and data was obtained from inventory databases. The analysis showed that energy consumption and sludge disposal have the most relevant environmental impacts, and increasing complexity increases the operational costs. Ioannou-Tofta et al. [113] also analysed a membrane bioreactor for the treatment of urban wastewater, and obtained similar conclusions concerning energy consumption, but also concluded that the materials used in the materials are also relevant to the overall environmental impact. The authors also concluded that the characteristics of energy mix are also relevant.

Bayer et al. [114] performed a LCA study of a combined membrane and liquid–liquid reactive extraction process for the removal of phenolic compounds from wastewater. Because it is a new technology, the main work goals are the identification of the optimal equipment sizes and operational conditions. The treatment process was modelled using MATLAB and the environmental impacts were evaluated using the Gabi software. Tangsubkul et al. [115] examined the influence of the operating conditions in the environmental performance of microfiltration processes used in WWT plants. Several options for the chemical cleaning of the membranes were considered. The FU is 1000 m^3 of wastewater, and seven environmental indicators were evaluated using equivalency factors adequate for Australian conditions. The results show that the lowest environmental impacts occur for low flux and high transmembrane pressure, and the choice of the cleaning chemicals can have a significant impact.

Razali et al. [116] analysed the environmental impact of the wastewater generated in membrane production, which can be a significant problem. Although the authors did not perform an LCA study, the results are relevant from a life cycle perspective as they can be used to select the most adequate WWT technology for membrane production processes. Several types of adsorbents were experimentally studied, and the results show that it is possible to treat the water for reuse in the membrane production process, significantly reducing the water needs for the process.

The sustainability of water treatment processes was also considered in the literature. Normally, the membrane is included in the process and not analysed in detail. An exception is the works of Pretel et al. [117, 118] that studied the environmental and economic sustainability of submerged anaerobic membrane reactor for treating urban wastewater. The analysis combined simulation of steady-state performance with LCA and LCC. A comparison with commonly used WWT methods was done. Results show that the membrane reactor significantly reduces the overall process's operational costs and environmental impacts.

Balkema et al. [119], Kalbar et al. [120], and Plakas et al. [121] proposed several methodologies to assess the sustainability of WWT systems based on different technologies. The indicators are selected based on their use in practice, and are calculated whenever possible based on the life cycle of the treatment system. The frameworks are intended for use in any process, including those with membrane systems. Kalbar et al. [120] and Plakas et al. [121] also proposed an aggregation scheme based on the application of weighting factors to the several indicators, to facilitate the ranking of the various technologies and decision-making.

Chen et al. [122] performed a critical review of the sustainability of recycling water schemes, including the WWT process. Several environmental assessment tools were reviewed including LCA, and their strengths and weakness were evaluated. The authors concluded that when LCA is used to select WWT technologies a better assessment of the overall process sustainability is performed.

2.3.2 Other Applications

For other processes besides water processing systems, in which membranes are key part of the system, the application of LCA has been limited. However, some LCA studies can be found in the literature in various areas besides water treatment. Some of them are described below by area of application.

2.3.2.1 Food Processing

Food processing is an area where membranes are used extensively, and where LCA is being used increasingly. For example, Omont et al. [123, 124] compared the environmental impact of two milk protein separation processes: chromatography and membrane filtration (micro- and ultrafiltration). The raw material is whey generated as a waste from normal dairy processes, considering all processes needed to obtain the final product. A FU corresponding to the daily quantity of milk processed in a French dairy (583 m^3). Environmental impacts were assessed using the IMPACT 2002+ methodology and SimaPro software for the calculations. The comparison results show that the membrane process is somewhat better than the chromatographic process, in particular, in the human and resources impact categories.

Aldaco et al. [125] and Margallo et al. [126] considered the partial dealcoholization of wines, comparing the environmental performance of several membrane-based technologies using the LCA methodology. A cradle-to-gate study was done, for a FU of 1 m^3 of dealcoholized wine. The studies concluded that reverse osmosis has high consumption of energy and may damage the wine quality, having the authors propose a new membrane technology that reduces those problems. Moreover, the normally used processes also have higher resources consumption, and the ability to valorize the wastewater generated is important in the overall system sustainability. Notarnicola et al. [127] applied the LCA methodology to a grape must concentration used to minimize the natural raw materials variability in a southern Italy winery. The process is based on reverse osmosis and the analysis uses primary data from industrial practice. A FU of 1 m^3 of wine (Rose Bombino) with a alcoholic degree increased from 10.5 to 11.5 was considered. Data was obtained from inventory databases. Eleven environmental indicators were evaluated using the CML methodology. The study concluded that energy consumption and membrane cleaning are the main operations in terms of environmental impacts. From the data, it was possible to identify the operational conditions for which the environmental impact is minimized and propose improvements to ensure that.

2.3.2.2 Gas Processing

Adbel-Salam and Simonson [128] considered a novel system to reduce the air humidity in air conditioning systems based on a membrane that isolates the desiccant and allows the removal of the water. Although the article does not present the results of an LCA study, the energy consumption and life cycle costs of the proposed system were compared with conventional systems, showing improvements in both aspects.

Gas separation is another area where membranes are also extensively used in various contexts. Cuéllar-Franca and Azapagic [129] performed a critical analysis of the state of the art on the available technologies for carbon capture, storage and utilization. Membranes are a good option capture CO_2, and depending on the impact category they are better than other options. The comparison between the various studies shows that significant reductions in the greenhouse gases emissions from power plants more than 50% are achievable. However, for other environmental indicators the sequestration can actually aggravate their values. The energy consumption is a disadvantage for membranes technologies that show correspondingly the higher global warming potentials.

Zhang et al. [130] compared three post-combustion carbon capture technologies, including a membrane system and a hybrid membrane-cryogenic process, from an energetic and life cycle perspectives. The performance of the capture systems was assessed by simulation. The results show that the membrane processes, and in particular the hybrid systems, have lower energy consumption and environmental impacts when compared with solvent-based processes, in particular, based in MEA absorption. Also, Schreiber et al. [131] and Troy et al. [132] compared various technologies for carbon capture using LCA, having also concluded that membranes have the best environmental performance. Both works considered the production of the membranes and supporting equipment, having explored scenarios for power plant operation and CO_2 generation. Petrakopoulou et al. [133] used LCA to compare two processes for pre-combustion CO_2 capture: one a standard methane steam reformer and the other a catalytic membrane used to remove the hydrogen from the natural gas. The results show that both processes have similar environmental impacts and both have to be improved in terms of efficiency to be viable options to be included in existing power plants.

2.3.2.3 Sustainability Evaluation

LCA methodology is currently seen as the most adequate framework to assess the sustainability of a product or process [134–136]. Most of the environmental indicators defined in a LCA study can be used as sustainability indicators, and the inventory analysis process and the impact assessment methodologies are also relevant. Thus, LCA is also applied to assess the sustainability of membrane systems, aiming to identify hotspots and improve their sustainability performance.

One example is the article by Szekely et al. [137], in which the sustainability of organic solvent nanofiltration is assessed based on a LCT perspective. The authors analysed all the steps of the membrane process, starting with the production of the membranes, process operation and end-of-life options for the membranes and other process units. Energy consumption, carbon footprint and operational parameters were the main indicators used in the evaluation. The various options and process characteristics, in each life cycle stage are compared with each other based on an extensive analysis of the literature in order to determine which ones are better and which operating conditions are desirable.

Criscuoli and Drioli [138], and Brunetti et al. [139] analysed the utilization of membrane processes to increase the sustainability of industrial process, in particular, in the water and gas treatment when compared with other options also used in industrial practice. Although the sustainability evaluation is not directly based on an LCT approach, some of the indicators are calculated taking into account the overall system and its performance. The indicator's main goal is to account for process intensification due to utilization of membranes, when compared with other processes, and serve as a decision-making instrument in the retrofitting of existing or new units and/or processes for which membranes may be viable option. Pal and Nayak [140] used a similar but simpler approach in the analysis of a membrane process for the production of acetic acid from waste cheese whey. The analysis focused on the process operation and was restricted to the equipment costs, operational and energy expenses.

2.4 Conclusions

This chapter presented a description of the principal principles of the LCA methodology, and how it has been applied to systems where membrane units are at the core of process or perform significant tasks, with a focus in water processing systems, either for human/industrial consumption or for WWT. As stated above, membranes are already extensively used in various processes and production systems. It is expected that the range of applications will increase in future, due the strong investment in research and development in the area, and the general belief that membrane systems are usually more sustainable [4]. Still, when designing and/or using membrane processes in practice is essential to support decisions based on the results of quantitative and objective tools, of which LCA methodology is currently the methodology of choice to evaluate the environmental impact of products/services or processes.

However, the analysis of the open literature shows that the application of LCA for evaluating membrane processes is still limited. This situation is odd as membranes are many times promoted as better options from an environmental point of view when compared with other processes and/or technologies. However, recent years have witnessed a growing interest in the application of LCA to evaluate membrane systems and/or technologies, as shown by the increasing number of works published in the last few years.

Some aspects that should be consider in future LCA studies of the systems involving membranes include:

- The manufacture and preparation of the membranes and/or corresponding modules should be considered more in detail and explicitly.
- The studies should take into account explicitly the membrane module maintenance and final disposal/recycling.
- More studies dealing with the sustainability of membrane systems are needed. Very few studies deal with the economic and social impacts of using this type of technologies. Also, many sustainability assessments are not based on a LCT approach.
- Care should be given to the selection of the FU and the environmental impact categories to be evaluated, in order to ensure comparisons as objective as possible between different studies.
- More Consequential LCA studies should be performed. As in many processes membranes will replace already existing processes or systems, its feasibility in terms of environmental impacts must take into account the existence of other technologies that perform the same tasks.

Acknowledgments Authors thank the financial support of project POCI-01-0145-FEDER-006939 (Laboratory for Process Engineering, Environment, Biotechnology and Energy—LEPABE) funded by FEDER through COMPETE2020—Programa Operacional Competitividade e Internacionalização (POCI) and by national funds through FCT. Authors also thank FCT for their support through provision of the research grants IF/01093/2014 and SFRH/BPD/112003/2015.

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Sustainable Membrane Technology for Water and
Wastewater Treatment
Figoli, A.; Criscuoli, A. (Eds.)
2017, XI, 380 p. 115 illus., 64 illus. in color., Hardcover
ISBN: 978-981-10-5621-5