Life Cycle Assessment of Emerging Technologies in Industrial Wastewater Treatment and Desalination

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Abstract Today, water scarcity affects human activities and ecosystems in many countries worldwide, leading to emerging new technologies to supply water from unconventional resources or enhance the recycling and reuse of available wastewaters. While, these emerging technologies might have environmental impacts, which are big challenges for sustainable development. Analyzing environmental impacts can help find the best and most sustainable choices that have the least negative impacts on ecosystems, resources, and human health. Life Cycle Assessment (LCA) is a tool to analyze and assess the environmental impacts for sustainability studies. LCA is essential in policymaking for developing desalination projects, especially in restricted areas like the Persian Gulf. An LCA study involves a total inventory and impacts of the energy and materials required across the industry value chain of the product, process, or service. This chapter is discussed the sustainability concept and takes a look at the technologies used in industrial wastewater treatment and desalination from a sustainability point of view. The general contaminants of industrial wastewater and saline water are presented. In addition, the LCA concept, framework, approaches, and Life cycle Inventory (LCI) methodology are explained. Various impacts of conventional and emerging industrial wastewater treatment and desalination technologies are presented to compare the technologies. Furthermore, prospects and challenges are discussed as a summary for the water engineering community.

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1 Introduction

Water plays a significant and vital role in life on our planet, and all living species are dependent on it (Naushad 2018). It has been reported that less than 0.4% of water resources are accessible to drink, and it has been estimated until the next three decades. The water shortage will be increased by more than 50% (Naushad 2018; Bordbar et al. 2020). In addition, global warming intensifies water scarcity due to the melting of polar icecaps (Naushad 2018).

Most water bodies are not suitable due to inappropriate contaminants such as salinity, bio-organisms, oily components, and heavy metals. Furthermore, industries have a significant and notable role in the pollution of water sources. Industrial wastewater is contaminated with dangerous components such as chemicals, organic and inorganic pollutants, dyes, and in particular heavy metal ions like Pb, Hg, Cr, Co, Ni, and Cd that may cause harmful effects on humans, aquatic, and animal life if they enter into the food chain (Naushad et al. 2017; Dehghani et al. 2021; Karri et al. 2021). Therefore, water treatment and desalination methods are used to treat industrial wastewater and saline water resources to supply fresh water.

Nowadays, emerging technologies are appearing by improving and combining technologies or integrating them with renewable energy resources (Bordbar et al. 2020). However, these plants directly and indirectly impact the environment, human health, Natural resources, and energy resources such as greenhouse gases (GHG) emission, global warming, acidification, eutrophication, toxicity, and natural and energy resource depletion, etc. It is necessary to analyze and assess these impacts and reduce them by improving the technologies. Life Cycle Assessment (LCA) is a systematic tool to assess and calculate these impacts, and it is based on the Life Cycle Sustainability Assessment (LCSA) framework of sustainable development (Shahabi et al. 2017; Klöpffer 2008). Sustainability is included from three key pillars: Environment, Economy, and Social (EES) (Zhang et al. 2020). In addition, energy is considered as another important parameter of sustainability.

To make a process or product sustainable, balancing environmental, economic, energy, and social aspects is necessary. Various parameters affect these aspects in water treatment, such as applied technology (hybrid, ZLD, membrane-based, thermal process, chemical process), entrance feed (brackish, seawater, contaminants of wastewater), contaminants of waste discharge, and applied energy resources (Fossil fuels, renewable energy). It has been reported that conventional plants are the costliest ones. In membrane-based plants, the concentration of feed is important. For example, the costs of desalinating brackish water are lower than seawater due to less energy consumption and fewer equipment requirements (Gude 2016). In addition, due to the different economic, environmental, and policy contexts, the costs are influenced by the location of plants (Sachs 2013; Gude 2016). Treatment plants cause significant effects on the environment due to releasing pollutants in the air, water, and soil (Younos 2005). LCA assesses them in several midpoint and endpoint impacts. Energy is another issue of sustainability studies. It has been observed that energy consumption is better managed in large-scale plants. For example, it has been seen that the average energy requirement is reduced by increasing the number of stages in Multi-Effect Distillation (MED) and Multi-Stage Flash (MSF) plants (Gude 2016).

This chapter is discussed the sustainability concept and takes a look at the technologies used in industrial wastewater treatment and desalination from a sustainability point of view. The contaminants of industrial wastewater and saline water are presented as an important factor in designing the plant and analyzing the impacts. In addition, the LCA concept, framework, approaches, and LCI methodology are explained. Impacts assessment is the main part of an LCA survey, while there are several midpoint and endpoint impacts. In this chapter, the studies on the impacts of emerging industrial wastewater treatment and desalination technologies are presented and compared to suggest the best technologies. Finally, future prospects and challenges are discussed to guide the water engineering community.

2 Sustainability in Industrial Wastewater Treatment and Desalination

Today, the phrases sustainability and sustainable development are frequently heard in media when a conflict occurs. Sustainability includes three key pillars: Economic, Environment, and, Social (EES) (Zhang et al. 2020). The process that has the most negligible EES effects over the life cycle is sustainable (Jaafar et al. 2007). LCSA is the newest framework to analyze and predict the sustainability of a process (Ciroth et al. 2011; Klöpffer 2008). This framework consists of:

- LCC: Life Cycle Costing
- LCA: Life Cycle Assessment
- SLCA: Social Life Cycle Assessment.

However, the application of LCSA is related to the availability of the Life Cycle Inventory (LCI) database. It is hard and time-consuming to collect data, so many tools, principles, and guidelines assess the EES impacts at different life cycle stages (Zhang et al. 2020).

Sustainable development balances economic performance, social justice, and environmental conservation (Naushad 2018). First-time World Commission on Environment and Development (WCED) determines sustainable development as satisfying today's requirements without endangering future potentials (WCED 1991).

The costs of processes are depended on various parameters (Council 2008). For example, it has been seen that conventional water treatment processes are cost-efficient only where there are accessible ground and surface water sources with reasonable distance (Gude 2015). According to the reports, brackish water desalination is the lowest final cost of the water process. It has been seen that the end costs of conventional methods are twice, but they consume energy by 5–25 times more. In large populations and industrial regions, the technologies should be updated; in this case, brackish or seawater treatment is a good choice, and due to the large-scale design, the energy usage becomes lower, especially for seawater desalination (Gude 2016). In areas with a large population with inaccessible water sources, end water costs and energy usage increase due to the transportation of raw water from a far distance. If seawater resource is accessible in these areas, seawater desalination is a good alternative. In this case, the energy usage and costs are comparable to conventional plants (Gude 2016).

Several European countries pay more water prices than other developed countries. It is due to different economic, environmental, and policy contexts. In developing countries, the government subsidizes the price of water (such as India and China). This causes excessive water consumption and is an unsustainable approach (Sachs 2013; Gude 2016). Several European countries have developed their water costs policy based on the environmental, socioeconomic, and full recovery of the costs in treatment plants. The removal of the water subsidy in Europe increased the price several times, and it was a solution to encourage people to consume less freshwater. In addition, because of huge investments in treatment infrastructure, the treatment costs and prices have fallen in Denmark and Germany (Gude 2016).

Energy consumption and environmental effects are important factors in water treatment. Energy consumption can be managed well in large-scale treatment systems. For example, by increasing the number of stages, energy usage will decrease in MED and MSF plants. As the same, Energy saving and water recovery will be improved by increasing the stages in membrane-based water treatment plants (Gude 2016).

Water treatment plants have notable direct and indirect effects on the environment and health. Fossil fuel consumption in these plants leads to air pollution and greenhouse gases (GHG) emissions that release CO, NO_x, and SO_x (Younos 2005). In addition, considerable amounts of chemical components such as anti-foams, anti-corrosion, anti-scaling, coagulants, and flocculants are used in pretreatment and post-pretreatment of the processes which are released into the river, groundwater, and sea affecting the ecosystem and water bodies (Lattemann and Höpner 2008; Qdais 2008) negatively. Furthermore, feed water's temperature and salinity may cause significant environmental challenges. It has been seen that conventional water treatment systems have more ecological impacts than membrane technologies, however, membrane water treatment plants have been used more chemical components in pre and post-treatment, and membrane cleaning steps (Gude 2016).

Technical, environmental, and economic issues are getting more attention than social issues, while installation and start-up of treatment plants have notable social effects. Lack of public reliance on water providers, making dust and noise pollution, and the effects on sea and beach can be considered social issues of water treatment plants (Gude 2016).

3 Contaminants of Industrial Wastewater and Seawater

The entrance of generated contaminants from agricultural, industrial, and commercial sources, landfills, and human activities pollutes the water bodies. Some industries are the main source of releasing toxic chemical components into the water streams. They include hydrometallurgy, mining, tanning, textiles, electroplating, dyeing, fertilizers, metallurgy, electrochemical and motor plants, metal fishing, and battery manufacturing (Olanipekun et al. 2014; Chen et al. 2015). Another source of water pollution is human activities due to the population increase, increasing landfills, generating sewage, deforestation, waste generation, and combustion (Owa 2013; Dehghani et al. 2021).

Contaminants are unwanted and frequently harmful and toxic components that decrease water quality. They can be originated from industries, natural resources, and mankind activities (Alqadami et al. 2016). In addition, salts are another undesirable contaminant found in seawater, brackish water, and other types of saline waters. The contaminants can be categorized into different types, such as heavy metals, organic and inorganic components, nutrients, dyes, biological substances, and salinity. These contaminants have been introduced in this section.

3.1 Heavy Metals

Industries are the major source of heavy metals discharge. Releasing heavy metals to nature is a dangerous environmental issues l which influences human health, plants, and animal life due to severe toxicity (Sharma et al. 2017). Due to bioaccumulation in living organisms, they can cause many diseases such as mutagenic disorders and cancer (Naushad 2018). Lead (Pb), mercury (Hg), nickel (Ni), arsenic (As), chromium (Cr), zinc (Zn), copper (Cu), cobalt (Co), cadmium (Cd), and antimony (Sb) are the main toxic heavy metals (Alqadami et al. 2017; Assadian and Beirami 2012; Ahmed et al. 2021). Today, developing countries are getting focused on removing toxic heavy metals to protect environments and human health (Ren et al. 2011).

Lead is an industrial heavy metal that is harmful to human health and is not biodegradable (Abdelwahab et al. 2015). It has been found in wastewater of metallurgy, refining, electronics, paint, and battery manufacturing industries. The most dangerous heavy metal is mercury. If it enters the food chain, bioaccumulation will happen easily. Mining, paper manufacturing, cement, and battery manufacturing are the sources of releasing mercury (da Cunha et al. 2016; Rahman and Singh 2016). Nickel is the raw material of alloys, steels, and battery manufacturing (Fukuzawa 2012). Combustion of fossil fuels and nickel production is a major source of releasing nickel into the environment (Naushad 2018). Cement, pesticides, color, and battery industries are the sources of releasing cadmium. The half-life of Cd has been predicted 10–30 years, and it is known as high-risk heavy metal (Bilal et al. 2016; Iqbal et al.

2016). Chromium is another toxic heavy metal, which has been found in tanning, electroplating, glass, and dyes industries (Dehghani et al. 2016). Arsenic is also a health-risk heavy metal found in deep areas of the earth (El-Moselhy et al. 2017). It enters the environment through natural and human activities, such as manufacturing glass, pesticides, mining, rural waste, and metallurgy (Jia et al. 2016; Hepp et al. 2017). Zinc is the common raw material in manufacturing due to its resistance to erosion. Zinc is used in electrical, metallurgy, and oil industries, and color industries to prevent erosion. Another heavy metal, which can be found in water sources, is copper. It has been found in wastewater of refining, mining, and electroplating industries. Cobalt is a metal that causes soil, water, and air pollution, and it may affect all living organisms by bioaccumulation. The main source of cobalt is mining, paints, and color industries. Antimony is known as high-risk toxic metal that is released by the burning of some commercial fuels, production of batteries, glycol, car parts, and coal mining (Naushad 2018).

3.2 Dyes

Around 10,000 different colors have been recognized and manufactured until now. It has been reported that near 700,000 tons of colors are produced annually and applied in several industrial sections categorized in cationic, anionic, and non-ionic dyes (Naushad 2018). In the production and manufacturing of products, dyes are entered into the environment by discharge effluents. Textile, food, paper, and tanning industries are the main sources of water pollution by dyes (Khan et al. 2020). If wastewaters that contain dyes enter the water sources, aquatic life will be endangered by chemical reactions (Zangeneh et al. 2015; Forgacs et al. 2004).

3.3 Biological Contaminants and Microbes

Biological contaminants, especially microbes, are another considerable parameter of water pollution caused by noxious microorganisms' activities in the water. The discharge of waste components by humans and animals causes waterborne pathogens. *Escherichia coli* (*E. coli*) is an important microorganism usually found in water. In addition, *E. coli* indicates the presence of other pathogens (especially *Vibrio cholerae*, *Salmonella typhi*, and *S. paratyphi*) in water. These contaminants lead to several diseases, and it is needed to control and remove them from water to protect humans and animals from toxic diseases (Ashbolt 2004; Fawell and Nieuwenhuijsen 2003).

3.4 Undesirable Chemicals

A group of noxious chemical materials is Endocrine-disrupting compounds (EDC). EDCs have various structures with a complex nature. The main source of EDCs is industrial wastewaters. Instructions have been set by organizations such as WHO, USEPA, and EU to determine a limitation amount for EDC in water. Removal of EDCs from wastewater is a key challenge due to the growth of industrial discharge effluent (Bolong et al. 2009).

Another root of water pollution is agricultural activities due to applying chemicals and pesticides. Agriculture has a significant role in environmental conflicts such as water shortage, pesticides release, soil erosion, water cycle changes, destroying aquatic life, food cycle changes, and releasing phosphorus and nitrogen components. The presence of nitrogen compounds in drinking water has a toxic effect on human health, causing disorders (Fawell and Nieuwenhuijsen 2003; Moss 2008).

3.5 Oily Content

Nowadays, the annual consumption of oil-based products is about 100 million tons (Abdullah et al. 2010). During drilling, extraction, oil production, and transportation by tankers, a high amount of oil is discharged to form oily waters. While, a small amount of oil content has significant impacts on human and aquatic life (Sabir 2015). The removal of oil content from oily water is a notable challenge in the oil industry, and this is a challenge for environmental experts. Regarding the regulations, the monthly average oil and grease concentration in the discharge stream should not exceed 40 ppm in the Persian Gulf region (Sabir 2015; Cambiella et al. 2006).

3.6 Salinity

The concentration of solved and dissolved salts in water is another environmental issue. It has been reported that more than 96% of water resources are saltwater (Gorjian and Ghobadian 2015). Dissolved solids and salt concentration in drinking water may cause diseases such as kidney failure. On the other hand, a saline hot spot may endanger the aquatic ecosystem, so there are strict environmental regulations for discharging the saline streams to avoid increasing the salt concentration by 10% in a 200 m distance from the discharge point.

Salinity is relevant to total dissolved solids (TDS) concentration, meaning higher salinity results in higher TDS. The salinity status of water are classified into the following categories (Mayer et al. 2005):

- Freshwater: salinity is less than 500 (mg/L TDS).
- Marginal water: salinity is between 500 and 1000 (mg/L TDS).

- Brackish water: salinity is between 1000 and 2000 (mg/L TDS).
- Moderately Saline water: salinity is between 2000 and 5000 (mg/L TDS).
- Saline water: salinity is between 5000 and 10,000 (mg/L TDS).
- Highly saline water: salinity is between 10,000 and 35,000 (mg/L TDS).
- Brine: salinity is over 35,000 (mg/L TDS).

4 Aspects of Life Cycle Assessment in Wastewater Treatment and Desalination

4.1 Goal and Scope

LCA is a systematic set of procedures, which analyzes and assesses environmental, economic, and social issues of products or processes. Triple sustainability pillars are related to the life cycle under the LCSA concept. Due to the purpose of projects, studies may include some or all of these three pillars (Guinée 2016). Environmental Life Cycle Assessment (ELCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA) are three forms of LCA (Traverso et al. 2012). ELCA is the most common indicator in studies, which was the early face of LCA in the early days of LCA appearance. The purposes of the LCA study include a comparison of products or processes, government policymaking, strategic planning, process improvement, marketing, consumer education, and product design (Demmers and Lewis 1996). LCA is a standardized methodology, which gives it its reliability and transparency. The ISO 14040 and 14,044 describe the four main steps of an LCA (Lee and Inaba 2004) as follows:

- Goal and scope definition
- Life cycle inventory analysis
- Life cycle impact assessment
- Life cycle interpretation.

The first step of an LCA is defining the goal and boundaries of the system. This step can affect the results of LCA and is named goal and scope by ISO 14040. This step includes determining goals of LCA, usage of results, and system boundaries that lead to defining a functional unit (Shaked et al. 2015). It should be clear that the purpose of LCA is based on which pillars of sustainability (environmental, economic, and social). The goal and scope of some studies in the literature are listed in Table 1.

Based on the system boundaries, the scope is determined. The scope determines the extent of the environmental, economic, and social impacts of components, raw materials, or the product, so there are a variety of scopes and system boundaries (ICCA 2020). Typical system boundaries are as follows:

- Cradle to grave: From raw material extraction through product use and disposal.
- Cradle to gate: From raw material extraction to the exit gate of the factory.

Table 1 A review of LCA in wastewater treatment and desalination. GWP: Global Warming Potential, AP: Acidification Potential, ODP: Ozone Depletion Potential, EP: Eutrophication Potential, POCP: Photochemical Oxidant Creation Potential, HTP: Human Toxicity Potential, ADP: Abiotic Depletion Potential, ETP: Ecotoxicity Potential, WD: Water Depletion, ERD: Energy Resource Depletion, LU: Land Use, MRD: Mineral Resources Depletion

No.	Process	Location	Software	LCIA Method	Functional Unit	Goal and Scopes	Approach		Impacts												Reference
							Mid-point	End-point	GWP	AP	ODP	EP	POCP	HTP	ADP	ETP	WD	ERD	LU	MRD	
1	RO	Sweden	GaBi	GaBi	NA	Environment, Cradle to cradle	✓		✓			✓	✓	✓		✓	✓				(Lundie et al., 2004)
2	RO, MSF, MED	Spain	SimaPro	CML, Eco-points, Ecoindicator	45500 m^3 treated water	Environment, Cradle to grave	✓		✓	✓		✓	✓								(Raluy et al., 2004b)
3	RO, MSF, MED, renewable energy	Spain	SimaPro	CML, Eco-points, Ecoindicator	1 m^3 treated water	Environment, Cradle to gate	✓		✓	✓		✓	✓								(Raluy et al., 2005a)
4	RO, MSF, MED	Spain	SimaPro	CML, Eco-points, Ecoindicator, BUWAL, ETH-ESU	45500 m^3 treated water	Environment, Cradle to gate	✓		✓	✓		✓	✓		✓	✓		✓			(Raluy et al., 2004a)
5	RO, MSF, MED	Spain	SimaPro	CML, Eco-points, Eco-indicator, BUWAL, ETH-ESU, IDEMAT	25000 hm^3 treated water	Environment, Cradle to gate	✓		✓	✓		✓	✓		✓	✓		✓			(Raluy et al., 2005b)
6	RO	United States	WEST	NA	123 ML treated water	Environment, Cradle to gate	✓		✓	✓		✓	✓					✓			(Stokes and Horvath, 2006)
7	RO, MSF, MED	Spain	SimaPro	CML, Eco-points, Eco-indicator, BUWAL, ETHESU, IDEMAT, Ecoinvent	45500 m^3 treated water	Environment, Cradle to grave	✓		✓	✓		✓	✓								(Raluy et al., 2004a)
8	RO, UF	France	GaBi	IMPACT 2002+	1 m^3 treated water	Environment, Gate to gate	✓		✓	✓	✓		✓			✓		✓			(Vince et al., 2008a)
9	RO	France		Ecoinvent, IMPACT 2002+	1 m^3 treated water	Economy, Cradle to gate	✓														(Vince et al., 2008b)
10	RO	Spain	SimaPro	Ecoinvent	1 m3 treated water	Environment, Cradle to gate	✓		✓	✓			✓	✓				✓			(Muñoz and Fernández-Alba, 2008)
11	NA	United States	SimaPro	Ecoinvent, ETH-ESU, BUWAL and	466 m^3 treated water	Environment, Cradle to gate	✓	✓													(Lyons et al., 2009)

(continued)

Table 1 (continued)

12	RO	Australia	SimaPro	Franklin library, Eco-indicator the Australian Greenhouse Gas method	1 GL treated water	Environment, Cradle to gate	✓		✓												(Biswas, 2009)
13	Review, renewable energy	United States	WEST, and GaBi	EIO-LCA	1 m³ treated water	Environment, Cradle to cradle	✓		✓	✓		✓						✓			(Stokes and Horvath, 2009)
14	RO	Spain	USES-LCA	EDIP	1 m³ treated water	Environment, Cradle to gate	✓						✓			✓					(Muñoz et al., 2009)
15	RO	Spain	SimaPro	Ecoinvent, CML, FEI indicator, CED	1 m³ treated water	Environment, Cradle to gate	✓		✓	✓	✓	✓	✓		✓			✓			(Muñoz et al., 2010)
16	WWTP	Spain	SiSOSTA QUA	CML	1 m³ treated water	Environment, Cradle to cradle	✓		✓	✓	✓	✓			✓	✓	✓	✓			(Pasqualino et al., 2011)
17	RO	Spain	SiSOSTA QUA	CML	1 m3 treated water	Environment, Cradle to gate	✓		✓	✓	✓	✓			✓	✓	✓				(Meneses et al., 2010)
18	RO	Germany	GaBi	SETAC guidelines	1 m³ treated water	Environment, economy, social, Cradle to gate	✓		✓												(Beery et al., 2010)
19	RO, RO-UF	Germany	GaBi	NA	1 m³ treated water	Environment, economy, Cradle to gate	✓		✓		✓					✓					(Beery and Repke, 2010))
20	RO	Germany	Excel	NA	1 m³ treated water	Environment, Cradle to gate	✓		✓												(Beery et al., 2011)
21	RO, MSF, MED	United States, SGP, Spain	SimaPro	Ecoinvent	1 m³ treated water	Environment, Cradle to gate	✓	✓	✓	✓	✓		✓	✓	✓	✓					(Zhou et al., 2011a)
22	RO, Memstill	Spain	GaBi	Ecoindicator, CML, Ecopoints	1 m³ treated water	Environment, energy, Cradle to gate	✓														(Tarnacki et al., 2011)
23	RO	United States	SimaPro	CML, TRACI, US Ecoinvent	1 m³ treated water	Environment, Cradle to gate	✓		✓	✓	✓	✓	✓	✓		✓					(Zhou et al., 2011b)
24	RO	Spain		CML, Ecoinvent	1 m³ treated water	Environment, economy, Cradle to gate	✓	✓	✓												(Salcedo et al., 2012)
25	PV RO, Solar still	United Arab Emirates	SimaPro	Ecoinvent, Eco-indicator	1250 L/day treated water	Environment, Cradle to gate	✓	✓	✓	✓	✓	✓				✓		✓	✓	✓	(Jijakli et al., 2012)

(continued)

Table 1 (continued)

26	RO-Memstill	Spain		Eco-indicator, CML, Ecopoints, Ecoinvent	1 m^3 treated water	Environment, Cradle to gate	✓	✓	✓	✓	✓	✓			✓	✓					(Tarnacki et al., 2012)
27	RO, UF, NF Hybrid	United States	SimaPro	CML	1 m^3 treated water	Environment, Cradle to gate	✓	✓	✓	✓	✓	✓	✓	✓	✓						(Hancock et al., 2012)
28	MSF, MED, VC, RO	United States	EIO-LCA	US EOI data	1 kWh energy	Environment, economy, Cradle to gate	✓		✓												(Norwood and Kammen, 2012)
29	Ion exchange, RO	South Africa	SimaPro	Ecoinvent, CML	1 ml boiler feed	Environment, Cradle to gate	✓		✓	✓		✓		✓	✓		✓				(Ras and Von Blottnitz, 2012)
30	UF, RO	Denmark	GaBi	EDIP	1 m^3 treated water	Environment, Cradle to gate	✓										✓				(Godskesen et al., 2013)
31	Solar RO	Spain		CML, Ecoindicator	NA	Environment, Cradle to gate	✓	✓	✓	✓	✓					✓		✓	✓	✓	(Antipova et al., 2013)
32	RO, MSF	SGP	NA	USEtox	1 m^3 treated water	Environment, Cradle to gate	✓														(Zhou et al., 2013)
33	RO, hybrid UF-RO	United Arab Emirates	SimaPro	Ecoindicator	1 m^3 treated water	Environment, Cradle to gate	✓	✓	✓	✓	✓	✓				✓		✓	✓	✓	(Al-Sarkal and Arafat, 2013)
34	Tertiary treatment	Spanish MED sea	NA	Ecoinvent, CML	1 m^3 treated water	Environment, Cradle to gate	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓			(Amores et al., 2013)
35	TVC-MED, MSF, RO, MVC	Italy	NA	EPD system framework	1m^3 treated water	Environment, Cradle to distribution	✓		✓	✓	✓	✓	✓				✓	✓			(Del Borghi et al., 2013)
36	RO	Australia	SimaPro	Australian database, Ecoinvent, IPCC	1 m^3 treated water	Environment, Cradle to gate	✓		✓									✓			(Shahabi et al., 2015a)
37	RO renewable energy	Australia	SimaPro	Australian database, Ecoinvent, IPCC	1 m^3 treated water	Environment, Cradle to gate	✓		✓												(Shahabi et al., 2014)
38	WWTP	Denmark	SimaPro	ReCiPe	1 m^3 inlet water	Environment	✓					✓	✓								(Niero et al., 2014)
39	WWTP	Australia		ReCiPe	1 year	Environment, Cradle to gate	✓		✓	✓	✓		✓	✓		✓	✓	✓		✓	(Lane et al., 2015)
40	FO	United States	SimaPro	TARCI	1 barrel O and G pit water	Environment, Cradle to gate economy	✓		✓	✓	✓	✓				✓		✓			(Coday et al., 2015)

(continued)

Table 1 (continued)

41	RO	Australia	SimaPro	EOI-LCA, CML	1 m^3 treated water	Environment, economy, Cradle to gate	✓		✓	✓	✓	✓	✓	✓	✓	✓				(Shahabi et al., 2015b)
42	RO	Australia	SimaPro	Ecoinvent, CML	1 m^3 treated water	Environment, economy, Cradle to gate	✓		✓	✓	✓	✓	✓	✓	✓	✓				(Shahabi et al., 2015c)
43	RO	Iran	SimaPro	Ecological scarcity	1 ha tomato farm	Environment, economy, Cradle to gate	✓													(Karami et al., 2017)
44	RO, FO, RO-FO	Global	NA	NA	1 m^3 treated water	Economy, Cradle to gate	✓													(Linares et al., 2016)
45	MED, RO	China	GaBi	CML, USEtox model	1 m^3 treated water	Environment, Cradle to gate	✓		✓	✓		✓		✓	✓					(Li et al., 2016)
46	CDI	Taiwan	SimaPro	Ecoinvent, CML, CED	1 m^3 treated water	Environment, energy, Cradle to grave	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓		(Yu et al., 2016)
47	RO, renewable energy	Tunisia	NA	Embodied Energy (EE) or Primary Energy Requirement (PER)	1 m^3 treated water	Environment, Cradle to gate	✓											✓		(Cherif et al., 2016)
48	Renewable energy	United States	EXCEL	GT PRO, PEACE	Per unit of consumed energy	Environment, economy, Cradle to gate	✓		✓											(Cherchi et al., 2017)
49	Hybrid FO-NF	Australia	SimaPro	Ecoinvent	100000 m^3 treated water	Environment, economy, Cradle to gate	✓		✓		✓	✓		✓		✓		✓	✓	(Kim et al., 2017)
50	RO	Australia	NA	CML	1 m^3 treated water	Environment, Economy, Cradle to gate	✓		✓	✓	✓	✓	✓	✓	✓	✓				(Shahabi et al., 2017)
51	MDC	United States	GaBi	ILCD, Ecoinvent	1 L treated water	Environment, Cradle to grave	✓		✓	✓	✓	✓	✓	✓	✓	✓				(Zhang et al., 2018)
52	RO, MSF	Kuwait		CML	1 ton of treated water	Environment, Cradle to gate	✓		✓	✓	✓	✓		✓	✓	✓				(Al-Shayji and Aleisa, 2018)
53	MSF, solar MED, RO, PV-RO	Kuwait	SimaPro	ELCD, CML	1 m^3 treated water	Environment, economy, Cradle to gate	✓		✓	✓	✓	✓	✓			✓				(Aleisa and Al-Shayji, 2018)
54	NA	Israel	SimaPro	Ecoinvent, ILCD, AHP	1 year	Environment, economy, Cradle to cradle	✓	✓												(Opher et al., 2019)

(continued)

Table 1 (continued)

55	ZLD, RO	Brazil	SimaPro	ReCiPe, CED, CML, EU25	1 m^3 treated water	Environment, Gate to gate	✓		✓							✓	✓	✓		(Ronquim et al., 2020)
56	RO	Persian Gulf	SimaPro	CML	1 m^3 treated water	Environment, Cradle to gate	✓		✓	✓	✓			✓	✓	✓				(Al-Kaabi and Mackey, 2019a)
57	MED	Northern Chile	GaBi	ReCiPe	1 m^3 treated water	Environment, Cradle to grave	✓		✓	✓	✓	✓	✓	✓		✓		✓		(Tarpani et al., 2019)
58	MSF, NF-MSF	Qatar	GaBi, VDS	ReCiPe	1 m^3 treated water	Environment, Cradle to grave	✓		✓		✓	✓		✓				✓		(Mannan et al., 2019)
59	RO, MED, MSF, solar energy	Kuwait, Algeria, Abu Dhabi, Spain, United States, Australia, Chile	GaBi	ReCiPe	1 m^3 treated water	Environment, Cradle to gate	✓		✓											(Alhaj and Al-Ghamdi, 2019)
60	MDS	Qatar	GaBi	ILCD	1 L treated water	Environment, Cradle to grave	✓		✓	✓	✓	✓	✓	✓	✓	✓				(Zhang et al., 2019)
61	RO	South Africa	SimaPro	ReCiPe	1 kL produce water	Environment, Cradle to grave	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	(Goga et al., 2019)
62	RO	SGP		ReCiPe	1 m^3 treated water	Environment, Cradle to grave	✓		✓	✓	✓		✓	✓			✓	✓		(Hsien et al., 2019)
63	RO	Qatar	GaBi	GaBi	1 m^3 treated water	Environment, Cradle to gate	✓		✓	✓	✓	✓	✓	✓	✓	✓				(Al-Kaabi and Mackey, 2019b)
64	Hybrid solar\wind RO-RED		GaBi	Ecoinvent	1 kWh energy	Environment, Cradle to gate	✓		✓						✓					(Tristán et al., 2020)
65	RO, Hybrid FO-RO, Hybrid UF-RO	Masig Island	WAVE, Hysys		-	Economy,	✓													(Pazouki et al., 2020)
66	ZLD	Europe	NA	NA	1 zero brine demo plant	Environment, Cradle to gate	✓													(Tsalidis et al., 2020)
67	RO	Malaysia	SimaPro	Ecoinvent	1 m^3 treated water	Environment, Cradle to grave		✓												(Abdul Ghani et al., 2020)

(continued)

Table 1 (continued)

68	RED, renewable energy	NA	OpenLCA	Ecoinvent	1 kWh energy	Environment,		✓	✓	✓	✓		✓	✓		✓				(Mueller et al., 2020)
69		Egypt	GaBi	GaBi	1 m^3 treated water	Environment, Cradle to gate	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓			(Morsy et al., 2020)
70	RO, IPR, RWH	Brazil	OpenLCA	Ecoinvent, ReCiPe	1000 m^3 treated water	Environment,	✓	✓		✓	✓	✓	✓		✓	✓	✓			(Tarpani et al., 2021)
71	RO		SimaPro	ReCiPe	1 m^3 treated water	Environment, Cradle to grave	✓	✓	✓	✓	✓				✓		✓	✓	✓	(Gao et al., 2021)
72	RO, FO-RO, UF-RO	Australia	WAVE	Ecoinvent	1 m^3 treated water	Environment, Gate to grave	✓	✓	✓	✓	✓	✓	✓	✓	✓					(Pazouki et al., 2021)

- Gate to gate: Start in a point (for example, raw material input at the gate of a factory) and end at a point (for example, the final product exportation gate of the factory).

In addition, there are other approaches, such as Cradle to cradle, that complete LCA boundary. LCA researchers use cradle to cradle for the cradle to grave approach that at the end of life, the final product is recycled (ICCA 2020).

4.2 Functional Unit (FU)

The second step of LCA is determining functional units (Klöpffer and Grahl 2014). A functional unit is a reference unit that expresses the system's performance numerically. Also, all midpoint and endpoint indicators in an LCA study are reported based on the selected FU (Shaked et al. 2015). For example, in water treatment research, the goal is to produce treated water. FU can be one of the following examples:

- 1 m^3 treated water
- 1000 glass bottles of treated water
- 5000 PET bottles of treated water
- 100 barrels of treated water.

The functional unit is the measurement basis of functions required to be supplied, such as fuel to provide 100 MJ energy, chemicals for pretreatment of 25,000 m^3 saline water, etc. This is to certify that comparing different processes or products in LCSA is on an equal basis. In addition, this is determined by how to define system boundaries. Each plant includes several functions, emissions, waste discharges, and chemical and utility consumption. Determining system boundaries means which of them are included in the study. For example, the environmental impacts of brine may not be taken into account in studies on desalination if the cradle to gate or gate to gate boundaries are chosen. A process may produce several products, while the functional unit is defined to fairly devote each product's impacts (Zhang et al. 2020).

4.3 LCA Approach and Methodology

International Standard Organization has provided some standards for LCA, including ISO 14040 and 14,044, which are followed by most of the research approaches and methodologies (Naushad 2018).

Impacts are classified into three categories: primary impacts, which include on-site impacts during the process; secondary impacts that are caused by other activities such as supplying energy and raw materials; and tertiary impacts that are determined as the effects after the process, such as the impacts of product use (O'Connor and Hou 2020). Primary effects can be measured, and secondary effects can be evaluated, while third-party effects are not measurable and only are presented by a unit-free value (Hauschild et al. 2017). Hence, Mid-point and End-point approaches are defined. The mid-point approach presents primary and secondary impacts in values with units, but the end-point approach reports a dimensionless value for impacts. The end-point analysis involves the environment, human health, and natural resources (Hauschild et al. 2017). At the same time, the impacts evaluated in the mid-point approach are presented in the next section. Determining the mid-point or end-point approach is important to choosing the LCA model. For example, CML, one of the most common life cycle impact assessment models, is a good choice for mid-point analysis, but it is not helpful for the end-point approach, while ReCiPe can be used for both mid-point and end-point analysis (Naushad 2018).

One of the LCA steps is Life Cycle Inventory Analysis (LCIA) that calculates the environmental impacts by determining each impact indicator from elementary flows in Life Cycle Inventory (LCI). LCIA includes the following steps:

Step 1: Choosing the relevant and suitable impact categories.

Step 2: Classification determines elementary flows into different impact categories.

Step 3: Characterization calculates potential impact indicators for each impact category.

Step 4: Normalization represents a relation of potential impact indicators to a reference.

Step 5: Grouping potential impact indicators based on specific rank or order.

Step 6: Weighting, which is assigning weights to each impact indicator due to relative importance.

Steps 1–3 are basic and mandatory steps of LCIA, and steps 4–6 are optional. Most LCIA studies only apply mandatory steps (Mu et al. 2020; Nieuwlaar 2004).

5 Environmental Impacts

5.1 Impact Assessment

Impacts assessment is the main part of an LCA survey. In this section, mid-point emissions are reported regarding the following impact indices (Hauschild et al. 2017):

- Global Warming Potential (GWP, or climate change)
- Ozone depletion
- Acidification
- Eutrophication
- Ecotoxicity
- Resources depletion
- Human toxicity
- Land use
- Water depletion

- Photochemical oxidation
- Particular matter formation
- Ionizing radiation
- Photochemical ozone formation.

In addition, end-point emissions are assessed into the three following impact categories (Hauschild et al. 2017):

- Natural resources
- Natural environment
- Human health.

In this chapter, these impacts are discussed under three categories: Environmental impacts, Impacts of resources, and, Impacts of Human health.

5.2 Global Warming Potential (GWP)

Global Warming Potential (GWP) impact (also known as Climate change) is the most noteworthy impact that reports greenhouse gases (GHG) emissions. CO_2 equivalent impact is reported in many LCA papers. This index also is called carbon footprint. In addition, the GWP index is also considered as an indicator to express the degree of development as well as energy loss. The primary effect of GHG is increasing infrared radiation adsorption, and the secondary effects are melting polar ices, increasing the sea level, and climate change (Hauschild et al. 2017). Figure 1 compares the global warming potential impacts of emerging industrial wastewater treatment and desalination technologies.

It has been found that the type of energy resources such as electricity and heat power has the most important effect on the GWP indicator. As shown in Fig. 1, the most negligible GWP impact is for Memstill® technology, which includes a solar still and membrane process with renewable energy power. The next one is RO technology with mixed electricity power included 98% wind power (Tarnacki et al. 2012). RO processes integrated with solar thermal energy that treated brackish and ocean water came in third and fourth, respectively (Stokes and Horvath 2009). The 5th is the RO process in Australia that uses wind power (Biswas 2009) and the 6th and 7th places are RO processes powered by photovoltaic energy (Stokes and Horvath 2009). All the characterizations of the third, fourth, sixth, and seventh plants are the same; therefore, it shows that solar thermal energy caused less GWP impact than PV resource and also, it has been revealed that wind power energy is a reliable low GWP effect resource.

The higher GWP emissions are for MSF and MED plants powered by natural gas (Raluy et al. 2004b) and the RO process, which consumes fossil fuels for electricity power (Biswas, 2009). This certifies that energy resource has the most prominent effect on GWP impact. To compare multiple processes as same as the functional unit, the scope of LCA should be the same. In this study, the scope of all studies is cradle

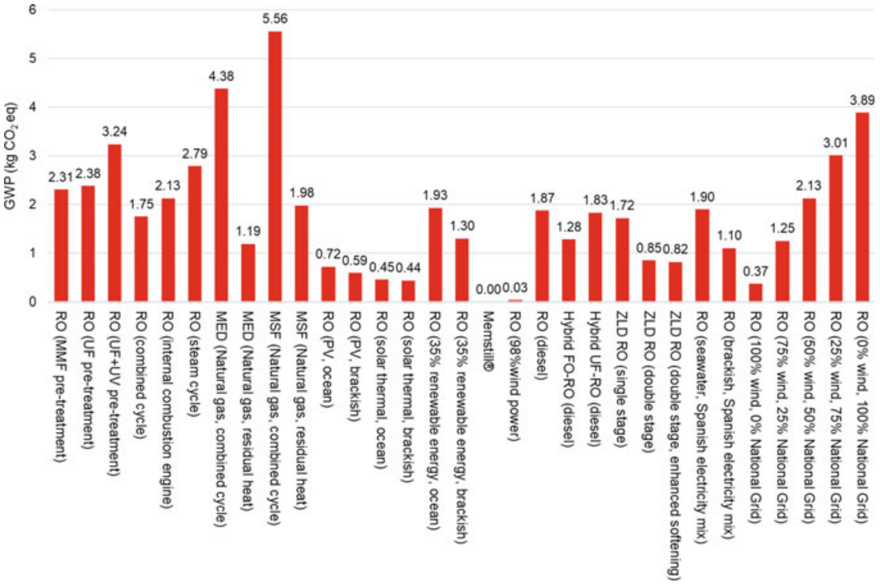

Fig. 1 Global warming potential impact of emerging industrial wastewater treatment and desalination technologies. FU = 1 m^3 treated water (Raluy et al. 2004b; Beery and Repke 2010; Stokes and Horvath 2009; Tarnacki et al. 2012; Pazouki et al. 2021; Ronquim et al. 2020; Muñoz and Fernández-Alba 2008; Biswas 2009)

to grave except ZLD plants (ZLD RO (single-stage), ZLD RO (double stage), and ZLD RO (double stage, enhanced softening). The scope of these plants is the gate to gate; therefore, analyzed values would be higher if their scope was cradle to grave.

5.3 Acidification Potential (AP)

Acidification potential impact refers to the influence of total emissions of acidic species (such as SO_x, NO_x, HCl, HF, and NH_4 into the air). The release of these emissions causes acidification in water and soil and consequently facilitates corrosion (ICCA 2020). The development of technologies for acidic gaseous removal, especially SO_2, can improve air quality and, as a result, reduce the acidification of water and soil (Klöpffer and Grahl 2014). Figure 2 compares the potential acidification impact of some emerging wastewater treatment and desalination technologies. Acidification potential impact has been reported by kg SO_x equivalent.

As depicted in Fig. 2, Memstill® technology reports the least acidification impact, and after that, RO powered by 98% wind energy is the best one (Tarnacki et al. 2012). RO (solar thermal, brackish), RO (solar thermal, ocean), RO (PV, brackish), RO (PV, ocean) are placed in the next places (Stokes and Horvath 2009). The most acidification impact refers to RO (seawater, Spanish electricity mix), MED (Natural gas, residual

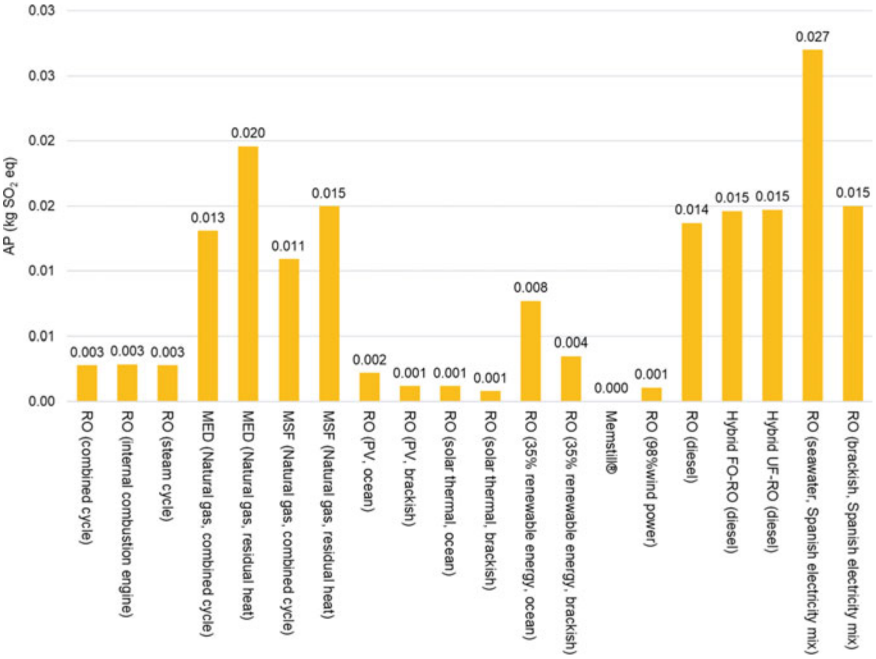

Fig. 2 Acidification potential impact of emerging industrial wastewater treatment and desalination technologies. FU = 1 m^3 treated water (Raluy et al. 2004b; Stokes and Horvath 2009; Tarnacki et al. 2012; Pazouki et al. 2021; Muñoz and Fernández-Alba 2008)

heat), MSF (Natural gas, residual heat), and RO (brackish, Spanish electricity mix), respectively (Raluy et al. 2004b; Muñoz and Fernández-Alba 2008). This shows that the energy source has a significant impact in acidification because of SO_x emissions of power production and fossil combustion.

5.4 *Eutrophication Potential (EP)*

Eutrophication potential impact (also known as Nutrification Potential (NP)) refers to releasing limiting nutrients (P and N contained components) into the water resources and soil that causes overgrowth of algae (ICCA 2020). Overgrowth of algae destroys biomass at the water resources and changes the character of the water body. This impact can be divided into aquatic eutrophication and terrestrial eutrophication. Aquatic eutrophication includes components in wastewater that have not been treated well and the entrance of wastewater into the water resources. At the same time, terrestrial eutrophication refers to the effects of NO_x and NH_4 gases (Klöpffer and Grahl 2014). Marine Eutrophication impact reports these effects as kg N equivalent, and freshwater eutrophication impact has been reported by kg P equivalent.

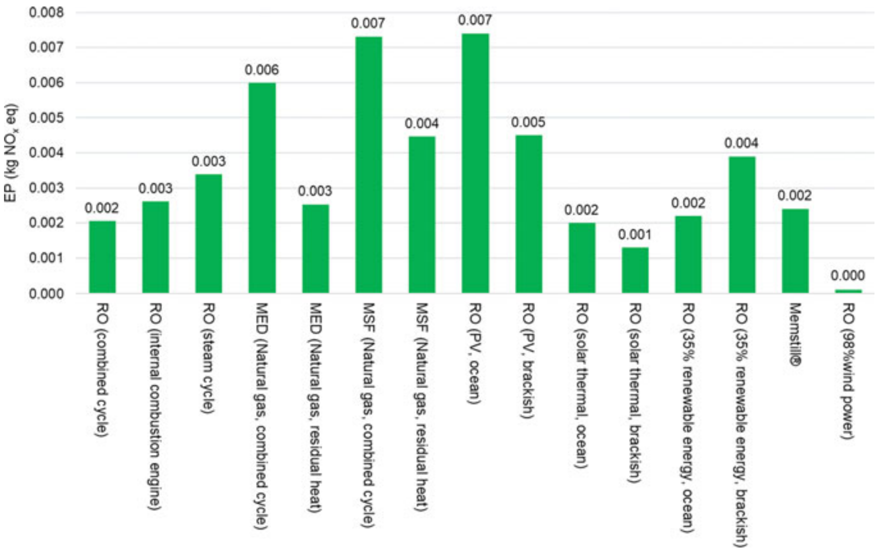

Fig. 3 Eutrophication potential impact of emerging industrial wastewater treatment and desalination technologies. FU = 1 m3 treated water (Raluy et al. 2004b; Stokes and Horvath 2009; Tarnacki et al. 2012)

According to Fig. 3, it has been found that the least NO$_x$ emission is for RO process powered by 98% wind power, and solar thermal RO plants to treat brackish and ocean water were ranked second and third, respectively. RO integrated with the combined cycle is ranked fourth. Because, in addition to energy resources, the contaminants in disposed waste have a noticeable effect on NO$_x$ emissions.

5.5 Ozone Depletion Potential (ODP)

Ozone depletion potential (ODP) includes the influences of releasing gases that destroy the ozone layer. The ozone layer is an artificial name for the middle part of the stratosphere, where the concentration of ozone is such that it prevents the passage of harmful UV to living cells. UV-B and C radiation can affect human health by leading to diseases such as skin cancer or lower crop yields (Baird 2012).

Trace components of HO$_x$ and NO$_x$ can cause a destructive reaction that causes ozone depletion. In addition, there was a challenge that supersonic airplanes could cause ozone layer depletion by NO$_2$ production in the 1970s. Then, the production of Freons and CFCs, by chlorine cycle as a refrigerant and spraying agents, caused Ozone depletion (Klöpffer and Grahl 2014). ODP impact reports these effects as CFC-11 equivalent.

Although the ozone depletion impact of water treatment plants has not been investigated in many studies, Fig. 4 compares a few processes. According to Fig. 4, it has

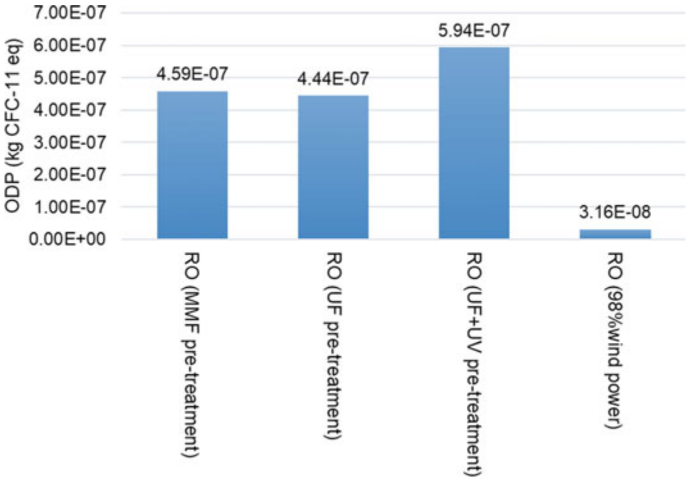

Fig. 4 Ozone layer depletion potential impact of emerging industrial wastewater treatment and desalination technologies. FU = 1 m3 treated water (Beery and Repke 2010; Tarnacki et al. 2012)

been found that the RO process by 98% wind power has the least ozone depletion impact. It can be concluded that the energy source is an essential factor in controlling and decreasing ozone depletion potential and CFC-11 eq amount. The next ranks are RO with UF pretreatment, RO with MMF pretreatment and RO with UF and UV pretreatment, respectively.

5.6 Ecotoxicity Potential (ETP)

Releasing toxic materials in the environment causes freshwater aquatic and marine aquatic ecotoxicity. The ecotoxicity potential (ETP) impact refers to the share of components that affect ecosystem substances. Heavy metals and organic pollutants are the main components (Tarnacki et al. 2012). This impact is divided into Freshwater Aquatic Ecotoxicity (FAETP) and Marine Aquatic Ecotoxicity (MAETP). Ecotoxicity impact reports these effects as 1, 4-DB equivalent.

Few of the above studies have investigated the ecotoxicity potential impact. In addition, differences in assessment method, scope and functional unit have made these studies incomparable. However, it has been observed that among the processes studied in the previous sections, the Memstill® process reports the lowest rate of ecotoxicity. In addition, the RO process powered by 98% wind power is in the next rank, indicating that the energy source plays a significant role in this impact category. The RO with UF pretreatment and RO with UF and UV pretreatment processes are also in the next ranks.

6 Impacts on Resources

6.1 Water Depletion

Freshwater is a vital resource, and water scarcity is a critical challenge today. LCA helps to determine a method to address water use correctly. The International Standardization Organization (ISO) determined a new concept to make an international standard for water footprint. The easiest way to define a water footprint is by applying water inventory analysis for the product of a process. By removing the amount of waste discharge from input water, the amounts of evaporated water, product use, and leakages are found, and consequently, water footprint can be defined and managed. LCA databases such as Ecoinvent, GaBi, etc., have determined water inventory analysis. It is noted that the inventories may be different depending on the database. These databases regularly just assess the input and output flows (Berger and Finkbeiner 2010).

In each process, requiring water is very important. The use of water affects the volume of water resources in the life cycle. Water depletion potential, also known as consumptive water footprint or water emissions footprint, represents the impacts of water usage. The main water resources are river, well, lake, and sea, subdivided into freshwater, saline water, and brackish water (ICCA 2020). The water consumption during the process, including the utility unit, has been assessed in this impact category, so the input water of plants has not been analyzed. Water depletion impact reports water use effects in m^3.

6.2 Energy Sources Depletion

Energy sources depletion (also known as Cumulative Energy Demand (CED)) refers to total applied energy over the process. This can be divided into fossil energy and renewable energy called Fossil Energy Demand or fossil depletion, and Renewable Energy Demand, respectively.

Fossil Energy Demand involves impacts of applying fossil-based energy such as coal, petroleum derivatives, natural gas, etc. The unit of Fossil depletion impact is kg oil equivalent.

Renewable Energy Demand refers to the effects of applied renewable energy (non-fossil fuel-based), including geothermal, wind, hydro, wave, photovoltaic, and solar energy (ICCA 2020).

6.3 Land Use

Another notable indicator in developing countries is changing the land from its primary state (grassland, forest, etc.) to a new state that affects GHG emissions. The changing usage is also known as direct land use. Indirect land-use refers to secondary land-use change because of primary land-use change by moving the commercial product and grown in a new location that caused GHG changes in the new land (ICCA 2020). Land use impact is reported in m^2.

7 Impacts on Human Health

The toxicity of materials on human health is not ignorable. Health safety should be assessed in each process and product. Human toxicity impact is one of the LCA indicators that refer to emissions and their effects on human health. Human toxicity and ecotoxicity have common resources, emissions, structure, and principles. Some emissions that release into the environment can endanger humans. In addition, during the production process, some emissions are released that endanger workers or consumers (Hauschild et al. 2017). The result of their influence on natural organisms is growing mortality, lowering mobility, lowering population growth, mutations, changing behavior, biomass changes, photosynthesis, etc. (Klöpffer and Grahl 2014). Human toxicity impact reports these effects as 1, 4-DB equivalent.

8 Future Prospects and Challenges

Industrial wastewater treatment and desalination technologies may cause severe environmental issues during their life cycle. Heavy metals, chemical components, biological components, salts, and other contaminants cannot be treated easily and can cause harmful and non-ignorable health issues by entering the food chain. In addition, water pollution destroys freshwater sources, and it accelerates water scarcity. Therefore, the governments should determine a policy and instructions to control the life cycle of water bodies. One of them is controlling and monitoring waste discharge of treatment plants (Naushad 2018). Another solution is to develop and build zero liquid discharge plants.

On the other hand, the energy source is a major parameter of environmental impacts. It has been seen that renewable energy resources are reliable and effective alternatives to fossil fuels to supply energy requirements in wastewater treatment and desalination plants. The chemical components impacts are lower than the impacts of the energy resources, but they are non-ignorable and should be considered in planning.

The LCA studies in the literature have not assessed the same environmental impacts. A few studies assessed the land use and salinity impacts. In addition, some of the studied system boundaries are incomplete. For example, the impacts of brine discharge have not been studied in many types of research with cradle to gate or gate to gate boundaries. New water treatment plants are built as collocated, cogeneration, and hybrid plants (Lee and Jepson 2021); Therefore, It is suggested that future studies focus on all dimensions of water-energy nexus impacts.

In addition to environmental aspects, economic and social impacts should be considered. Recently, LCA researchers have considered the LCSA framework for sustainability studies. Therefore, emerging LCA frameworks have a significant role in improving analyzing sustainability of industrial wastewater treatment and desalination plants.

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