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Quantifying the environmental sustainability of ultrafiltration membranes in desalination pretreatment processes using life cycle assessment

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ABSTRACT

This study delivers a comprehensive environmental sustainability assessment of ultrafiltration membranes in desalination pretreatment and advances a decision-support framework to mitigate manufacturing-related ecological burdens. The impact assessment was performed using life cycle assessment (LCA) in SimaPro V9.4 with a cradle-to-cradle approach. The Recipe method, incorporating midpoint and endpoint indices, along with the IPCC method, was used to evaluate the consequences of membrane fabrication via the phase inversion method. Material flows and energy consumption were modeled based on the operating conditions of the membrane manufacturing process. Sensitivity analysis was conducted to identify opportunities for technical improvements at an industrial scale. Results indicated that the most significant environmental impacts are related to terrestrial ecotoxicity and resource depletion. Electricity production notably contributed to most impact categories, especially global warming potential. The sensitivity analysis revealed that reducing electricity consumption at an industrial scale or switching to renewable energy sources could substantially decrease environmental impacts. Consequently, conducting a product sustainability assessment using LCA is vital for identifying environmental hotspots within a product's or process's supply chain, followed by process optimization through pollution prevention strategies and environmental performance improvements.

Highlights

- First LCA-based evaluation of UF membrane fabrication in Iran using the phase inversion method
- Quantitative midpoint and endpoint impact assessment in UF manufacturing stage via SimaPro
- Providing essential information for UF membrane fabrication on an industrial scale by Sensitivity analysis

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1. Introduction

Ensuring a sustainable supply of potable water is an enduring challenge for modern societies. Intensifying climate change, coupled with rapid population growth, has led to severe water scarcity in regions such as India, Jordan, and Mexico City (Salahshoor et al., 2022; Vatanpour et al., 2021). In Iran, this challenge is further exacerbated by limited freshwater availability, recurrent droughts, and contamination of existing water resources, all of which complicate water management strategies. Among the available technological solutions, desalination of seawater and brackish water has emerged as a pivotal alternative for augmenting freshwater supplies(Pazouki et al., 2021). Membrane filtration represents an advanced approach in water treatment and desalination, capable of mitigating variability in feedwater quality and reducing pollutant loads(Siefan et al., 2022). In desalination systems, seasonal fluctuations in source water often compromise operational efficiency. Integrating ultrafiltration (UF) as a pretreatment step stabilizes feedwater quality, enhances downstream performance, and prolongs membrane lifetime by minimizing fouling (Pazouki et al., 2021).

While membrane-based pretreatment offers clear technological benefits, its environmental implications—particularly during manufacturing—remain underexplored (Grossi et al., 2024). In practice, investment and operational cost considerations dominate decision-making for water, wastewater, and desalination projects, whereas life cycle cost (LCC) and environmental life cycle impact (ELCA) metrics are rarely integrated. Life cycle assessment (LCA) offers a scientifically robust framework for evaluating cumulative environmental burdens across all stages of a product's life, from raw material acquisition to fabrication (Çetinkaya and Bilgili, 2022). By combining environmental and economic indicators, LCA supports evidence-based decisions that minimize ecological harm while preserving cost-effectiveness (Lee and Jepson, 2021).

Existing LCA research in the desalination sector has predominantly addressed operational stages—often focusing on reverse osmosis (RO) configurations (Bordbar et al., 2022; Razman et al., 2023)—or the integration of renewable energy systems (Kaczmarczyk et al., 2024). Only a limited number of studies have investigated UF membrane fabrication, with findings indicating that solvent selection, additive use, and electricity sourcing are the primary contributors to environmental impacts (Prézélus et al., 2021).

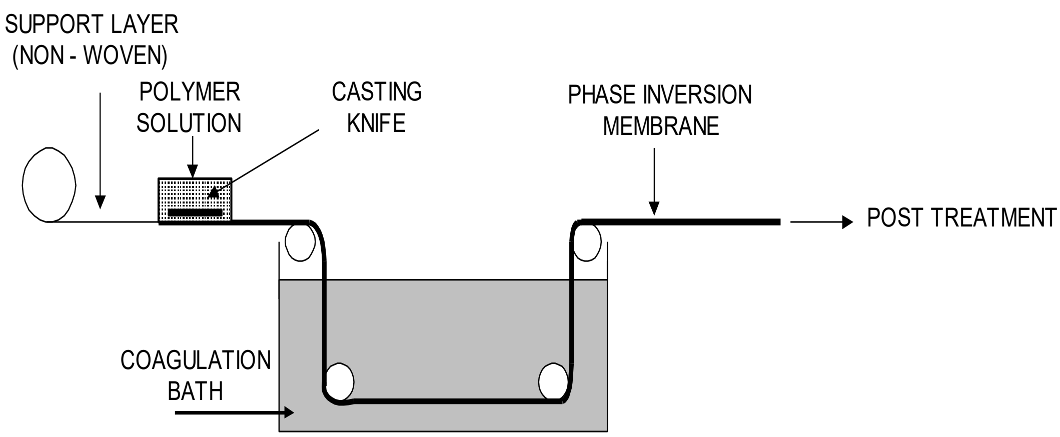
Moreover, research examining desalination plants in various Iranian regions—including the Persian Gulf (Bordbar et al., 2022), Chabahar, and Kangan (Bakhshayesh et al., 2020) — has evaluated the impact of operational parameters on the environmental profiles of existing facilities. However, an explicit and comprehensive LCA focused on UF membrane fabrication within the Iranian context has not yet been documented, marking a notable gap in current literature. Addressing this deficiency, the current study employs the LCA methodology via SimaPro software to quantify the environmental impacts associated with UF membrane production, utilized as a pretreatment step in desalination processes. This assessment includes detailed quantitative modeling of midpoint and endpoint environmental impacts arising from chemical usage and energy consumption.

2. Materials and Methods

2.1 Uf membrane fabrication

The phase inversion method (Fig. 1) was used to fabricate flat ultrafiltration membranes(Vatanpour et al., 2021). In this process, a specific proportion of Polymervinylidene fluoride (PVDF) was added to the solvent Dimethyl-formaldehyde and placed in an ultrasonic bath for 1 hour to achieve a homogeneous solution. Following this, Polyethylene glycol as a porous agent was added to the solution. Then, casting solution was placed on a stirrer for 24 h at 60°C. Subsequently, the degassed polymer solution was uniformly cast onto a glass plate with a controlled thickness of 170 micrometers. The cast films were placed in a distilled water bath as a non-solvent immediately after casting,until the phase inversion process was initiated and completed.

Fig. 1 Schematic of the semi-industrial fabrication process of UF membranes



2.2 Characterization of the UF membrane

Morphology characterization analysis was performed using a field emission scanning electron microscopy (FE-SEM) model LEO 1455VP and an AFM model VEECO, USA, for cross-section and surface roughness of the membranes, respectively. The surface area of 25 μm^2 was scanned to imagine the membrane surface and calculate the roughness parameters.

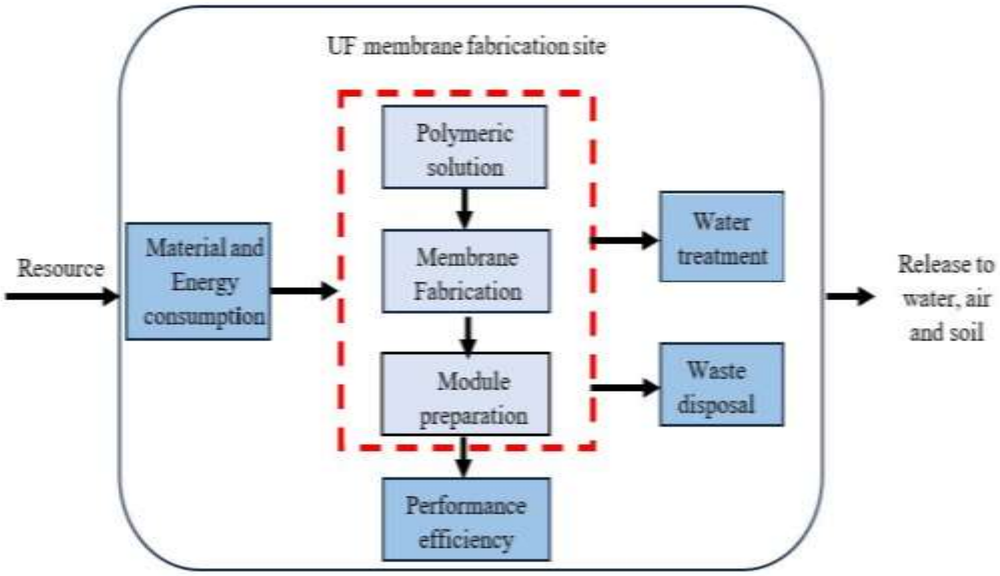
2.3 LCA methodology

In this study, the stability of the UF membrane during the manufacturing phase was evaluated using the ISO-standardized LCA framework(Kaczmarczyk et al., 2024; Skuse et al., 2023). This methodology comprises four sequential stages: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation. In the first stage, the goals and boundaries of this research and the functional unit of products as a basis for comparison were defined. In the second stage, the input and output data were collected according to the functional unit. Various LCIA methods were used in the third phase to quantify the environmental impacts of the products' life cycle. Finally, in the interpretation stage, LCIA results were analyzed in detail to identify the most significant environmental hotspots. All modeling and computations were carried out using SimaPro v9.4 software in conjunction with the EcoInvent database.

2.3.1 Functional unit and System boundaries

The functional unit for LCA was defined as "1 m^2 of UF membrane". Accordingly, all raw material requirements, energy consumption, associated emissions, and calculated environmental impacts within the LCA model were based on the functional unit of 1 m^2 membrane. The defined system boundaries encompass all material and energy flows associated with manufacturing 1 m^2 of UF membrane, as depicted in Fig. 2. A cradle-to-grave assessment approach was adopted, covering the entire process from raw material extraction and preparation through to membrane fabrication.

Fig. 2 System boundary of the life cycle assessment of the fabricated membrane module



2.3.2 Inventory data and limitations

The raw materials input and energy consumption during the manufacturing of the UF membrane were collected. Most LCA data were taken from the SimaPro database. However, some assumptions were made when the required data could not be found in the database.

The PVDF was replaced by 50% Tetrafluoroethylene (TFE) and 50% Polyethylene (PE), which was confirmed by Solvay representatives as acceptable for its environmental impact(Chong et al., 2018). The stoichiometric method was used for Lithium bromide (Eqs. 1 and 2) to enter data into the software(Prézélus et al., 2021).

$$LiOH + HBr \rightarrow LiBr + H_2O \quad (1)$$

$$Br_2 + SO_2 + 2H_2O \rightarrow H_2SO_4 + 2HBr \quad (2)$$

2.3.3 Environmental impact assessment (EIA)

The LCA modeling and the environmental impacts were estimated according to the ReCiPe 1.13 (H) and Intergovernmental panel on climate change (IPCC) 2013 GWP 100a(Prézélus et al., 2021; Skuse et al., 2023). The ReCiPe method, which considers both midpoint and endpoint approaches, is used to illustrate the impacts of activities on a wide range of environmental issues. It includes 18 midpoint impact categories and 17 endpoint impact categories. To facilitate the interpretation of the endpoint impact method, three categories are considered: human health, ecosystem quality, and resource. The IPCC 2013 GWP 100a method was selected to examine the contribution of 1 m^2 membrane manufacturing activity in global warming potential (GWP) and climate change in terms of CO_2 emission equivalent (CO_2-eq) with 100 years' time frame.

2.4 Sensitivity analysis

Variations in material and energy demands between laboratory-scale and industrial-scale Uf membrane production can significantly influence LCA outcomes. To account for these potential discrepancies, a sensitivity assessment was performed by altering the consumption of a key influential parameter—either material or energy—across a range of reductions up to 95%, while maintaining all other variables constant(Kim and Overcash, 2003).

3. Results and Discussion

3.1 UF membrane characterization

Fig. 3(a) illustrates the cross-section images of manufactured UF membranes with the final thickness of around 170 µm at two magnifications. As shown in Fig.3(a), both spongy and finger-like textures are observable in the membrane's structure(Vatanpour et al., 2021).

The AFM images were taken from the membrane surfaces to determine the surface roughness of the UF membrane, which is presented in Fig. 3-b. Some of the main roughness parameters, such as the roughness average (Sa), root mean square roughness (Sq), and the average of peak heights plus valleys depths (Sz) are shown in Table 1. These results, which are consistent with the study conducted by Vatanpour et al. (2021) indicate that the fabricated membrane has appropriate roughness(Vatanpour et al., 2021).

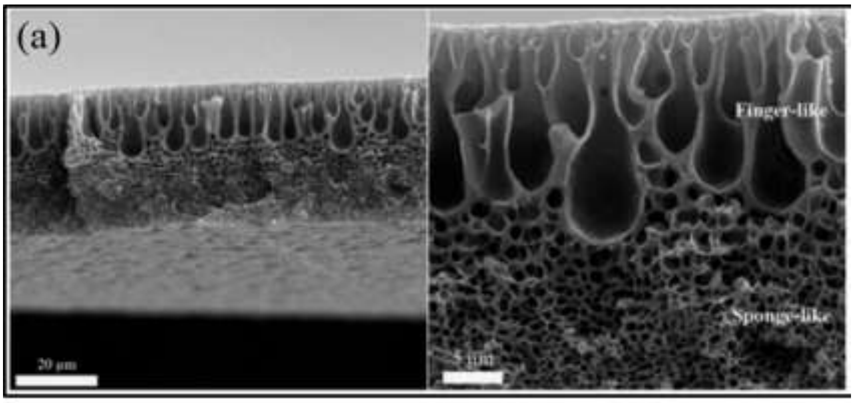


Fig. 3 UF membrane identification analysis: a) FE-SEM images of the membrane cross-section at two magnifications of 5 and 20 µm, and b) AFM analysis image

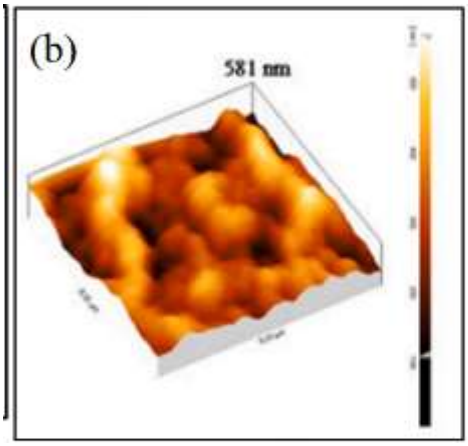


Table 1 Average roughness parameter of UF membrane

Roughness parameters	unite	value
S_a	nm	69.6
S_q	nm	86.8
S_z	nm	456

3.2 UF membranes EIA

3.2.1 EIA in the midpoint method

The use of chemicals and energy in industrial processes inevitably leads to the emission of pollutants that can adversely affect ecosystem health and overall environmental quality (Skuse et al., 2023). Influence of material and energy consumption analysis in UF membrane fabrication to various environmental impact categories was illustrated in Table 1 and Fig. 4. The data clearly indicate that the manufacturing process imposes. The analysis indicates that the most significant environmental impact in the categories of terrestrial ecotoxicity and global warming potential. As illustrated in Fig. 4, electricity consumption is the predominant driver across nearly all impact categories, accounting for approximately 52% of the total environmental burden. Notably, electricity's influence was substantial in all categories except for stratospheric ozone depletion and marine eutrophication. Specifically, in the context of terrestrial ecotoxicity—measured as 29.5 kg 1,4-dichlorobenzene (1,4-DCB) equivalents—energy consumption emerged as the primary contributor, with dimethyl formaldehyde playing a secondary role.

Table 2 Modeling results of environmental impacts 1m^2 of UF membrane fabrication in 18 categories of the midpoint method

Impact category	Unit	Total Value
Global warming	kg CO_2 eq	15.49494
Stratospheric ozone depletion	kg CFC11 eq	3.54E-05
Ionizing radiation	kBq Co-60 eq	0.459191
Ozone formation, Human health	kg NO_x eq	0.020015
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.010731
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.020645
Terrestrial acidification	kg SO_2 eq	0.030261
Freshwater eutrophication	kg P eq	0.001171
Marine eutrophication	kg N eq	0.000317
Terrestrial ecotoxicity	kg 1,4-DCB	29.42956
Freshwater ecotoxicity	kg 1,4-DCB	0.665343
Marine ecotoxicity	kg 1,4-DCB	0.825019
Human carcinogenic toxicity	kg 1,4-DCB	0.200695
Human non-carcinogenic toxicity	kg 1,4-DCB	4.169058
Land use	m^{2}a crop eq	0.097146
Mineral resource scarcity	kg Cu eq	0.01731
Fossil resource scarcity	kg oil eq	5.141024
Water consumption	m^3	0.028886

Fig. 5(a) illustrates the contributions of various substances to terrestrial ecotoxicity. The most significant impacts arise from the release of copper and zinc metals into the air, the discharge of bromine into aquatic environments, and the infiltration of cypermethrin into soil. Global warming (15.5 kg CO_2 eq) was mainly contributed by the emission of carbon dioxide 13.5 kg CO_2 eq (Fig. 5b), during combustion of fossil fuels for energy production, alongside contributions from methane, sulfur hexafluoride, and nitrous oxide. Coal-fired power plants are responsible for approximately 30 billion tons of CO_2 emissions annually on a global scale, making these gases primary agents of climate change. These midpoint impact findings align closely with reported in previous research(Çankaya & Pekey, 2024; Ribeiro et al., 2024)

Fig. 4 Contribution of materials and energy consumption to the environmental impacts of 1 m^2 of UF membrane in damage groups in the Recipe midpoint method

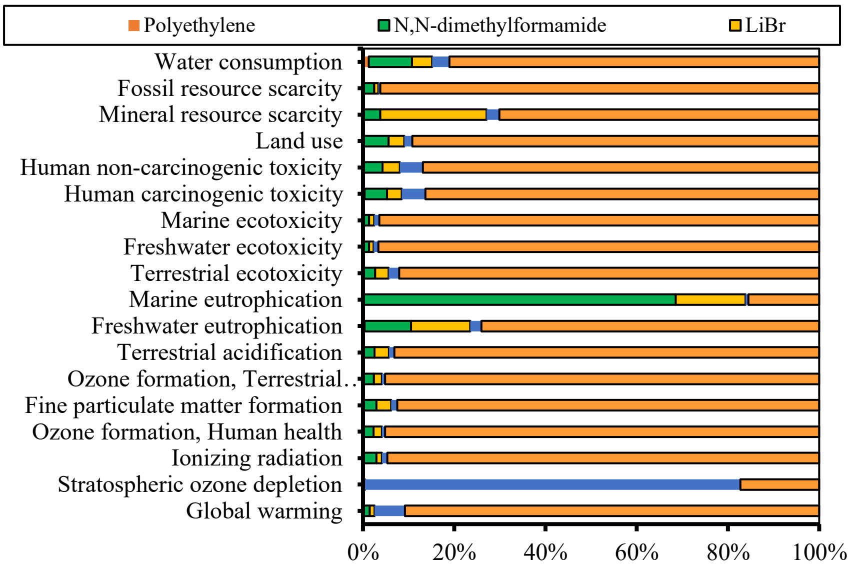
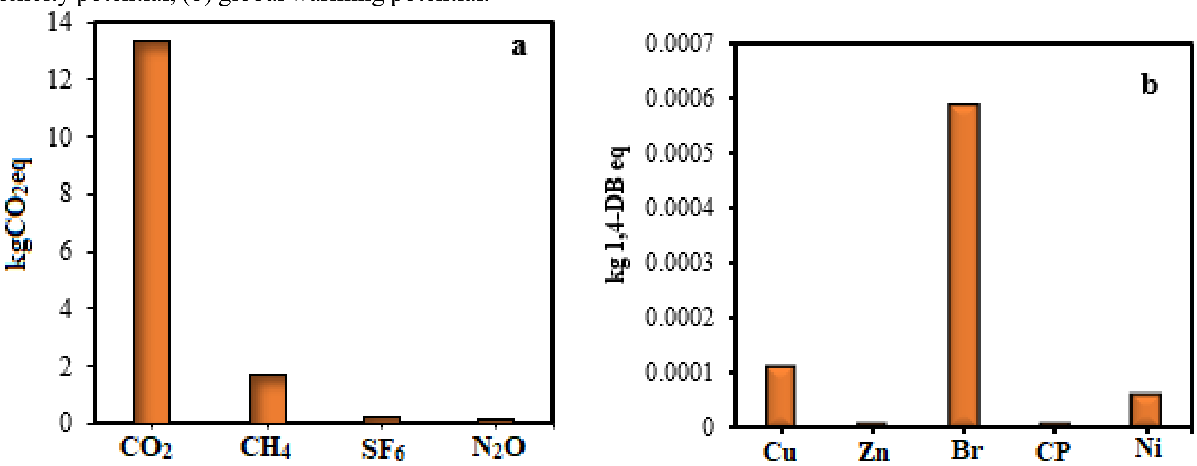
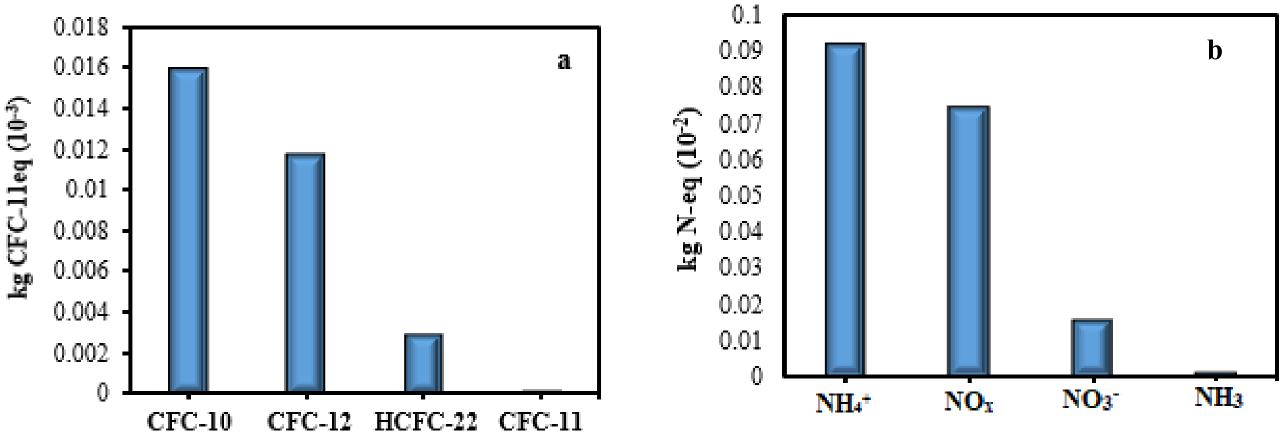


Fig. 5 Midpoint impact contributions of emissions from material and energy consumption in the fabrication of 1 m^2 UF membrane: (a) terrestrial ecotoxicity potential, (b) global warming potential.



In the stratospheric ozone depletion category, the most significant contribution—approximately 84% of the total impact—originated from the use of tetrafluoroethylene, corresponding to emissions of 3.54 × 10^{-5} kg CFC-11 equivalents. Electricity consumption accounted for the remaining 16% of the impact. As illustrated in Fig. 6 (a), CFC-10 and CFC-12 were identified as the dominant ozone-depleting compounds. For marine eutrophication, the production of 1 m^2 of UF membrane resulted in an environmental burden equivalent to 317 × 10^{-6} kg N equivalents. Of this, 70% was attributed to dimethyl formaldehyde, 15.2% to lithium bromide, and 14.8% to electricity consumption. As shown in on Fig. 6(b), ammonium ion emissions to both water and air were the primary contributors within this category, followed by nitrogen oxide, nitrate, and ammonia emissions—0.09, 0.07, 0.01, and 0.001 × 10^{-2} kg N equivalents, respectively. These patterns align with earlier studies by Prézélus et al. (2021), Bordbar et al. (2021), and (Bakhshayesh et al., 2020)

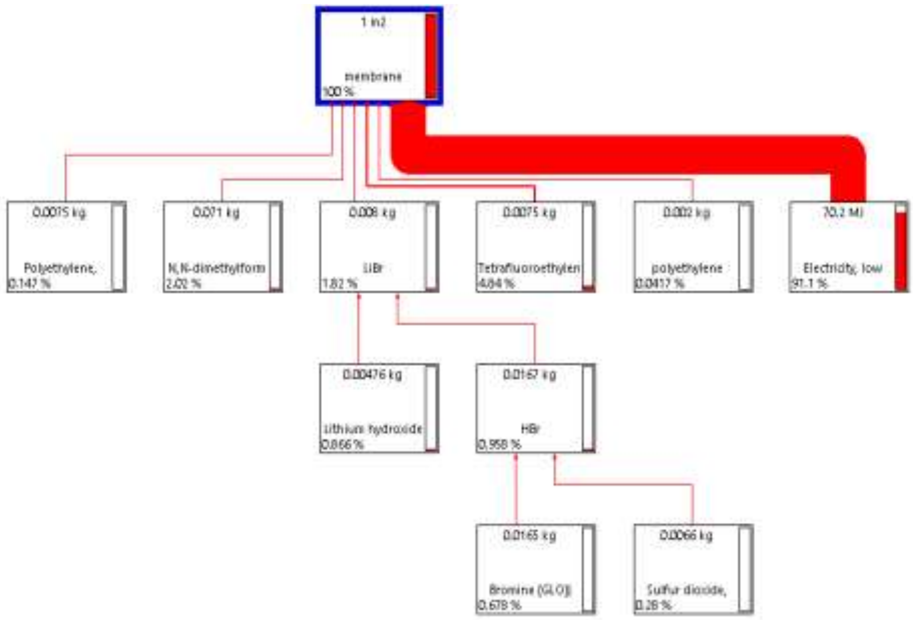
Fig. 6 Contribution of emissions from material and energy use in the production of 1 m² UF membrane to ReCiPe midpoint categories: a) stratospheric ozone depletion, (b) marine eutrophication.



3.2.2 EIA in the endpoint method

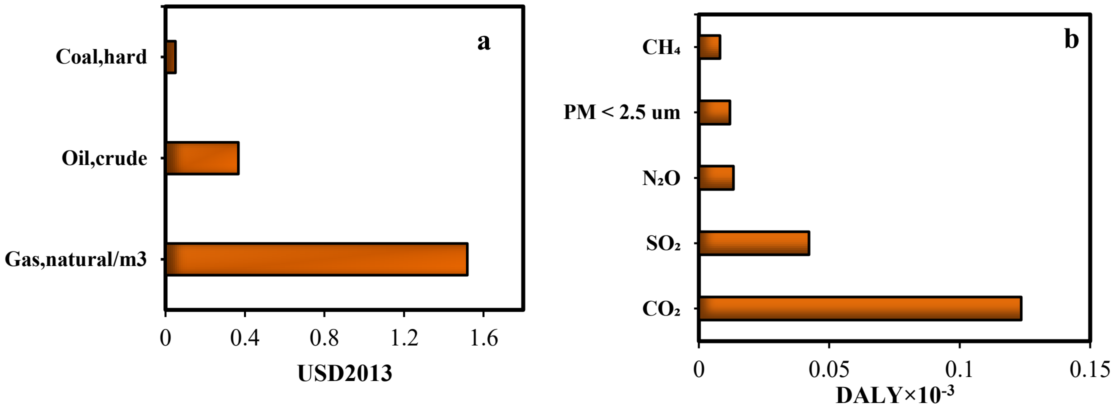
The ReCiPe endpoint analysis revealed that UF membrane fabrication exerted the greatest environmental impacts on resource depletion (1.9 USD), followed by impacts on human health (2.3×10^{-5} DALY) and ecosystem quality (5.5×10^{-8} species·yr). As shown in Fig. 7, electricity consumption accounted for over 90% of total damage across all endpoint categories, underscoring the dominant influence of fossil fuel–based power generation(Prézélus et al., 2021). Within the resource damage category(Fig. 8-a), natural gas (1.51 USD) and crude oil (0.36 USD) emerged as the primary contributors. These findings highlight the strong link between the extraction of non-renewable energy resources—particularly fossil fuels—and associated environmental degradation. The observed trends are consistent with previous studies (Ioannou-Ttofa et al., 2016; Martinez-Diaz et al., 2021; Singh et al., 2020) which reported comparable resource depletion impacts from crude oil and coal use in electricity production.

Fig. 7 Contribution of material and energy consuption to resource depletion in the fabrication of 1 m² UF membrane, based on ReCiPe endpoint assessment.



Following resource depletion, human health was the next most affected category. As shown in Fig. 8(b), key contributors to human health impacts included CO_2, SO_2, NO, particulate matter, and CH_4, primarily arising from electricity generation and Tetrafluoroethylene use during UF membrane fabrication. LCA results indicate that electricity consumption indirectly affects human health due to fossil fuel-based energy production (Abyar and Nowrouzi, 2020; Mathuriya et al., 2020). The extraction and combustion of fossil fuels release hazardous substances, including toxic gases, heavy metals, sulfur compounds, and polycyclic aromatic hydrocarbons, into the environment. Consequently, mitigating these environmental and health impacts requires improving energy efficiency, minimizing energy demand, and transitioning to renewable energy sources (Foteinis et al., 2018).

Fig. 8 Emissions from material and energy use in producing 1 m² of UF membrane, analyzed for endpoint modeling: (a) resource impacts, (b) human health impacts.



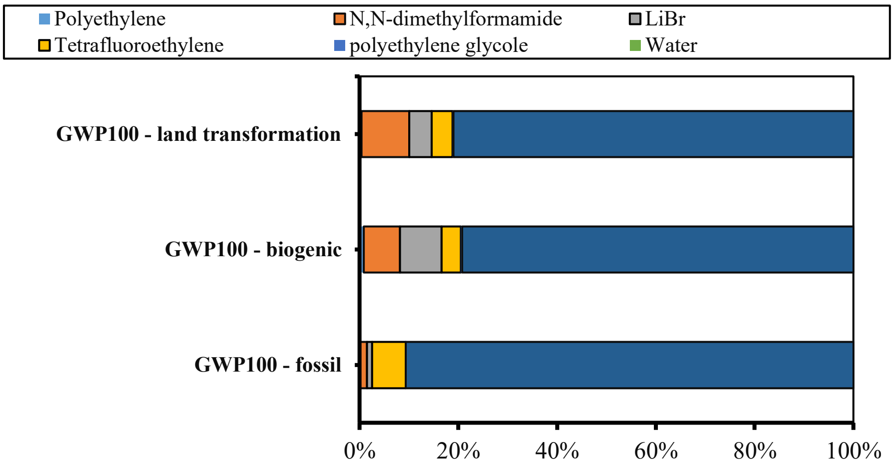
3.3 Global Warming Potential (IPCC method)

The IPCC-based assessment for 1 m² of UF membrane revealed CO_2 emissions of 15.3 kg CO_2-eq from fossil fuels, 0.0025 kg CO_2-eq from biogenic sources, and 0.0019 kg CO_2-eq from land transformation (Table 3). As shown in Fig. 9, electricity consumption, predominantly supplied by the fossil fuel-based national grid, was the largest contributor to global warming across all three IPCC impact categories. Following energy use, dimethyl-formaldehyde was identified as the primary contributor to CO_2 emissions within the land transformation and biogenic categories, aligning with results obtained using the ReCiPe method. These findings highlight the critical importance of transitioning to renewable energy to mitigate the environmental impact of UF membrane production (Bordbar et al., 2022; Martinez-Diaz et al., 2021).

Table 3 Results of analysis from IPCC modeling 1 m² of UF membrane fabrication (kg CO_2 eq)

Impact Category	Total Value
Fossil fuels	15.35
Biogenic fuels	0.0025
Land transformation	0.0019

Fig. 9 Relative contributions of materials and energy consumption to global warming potential during the fabrication of 1 m² UF membrane by IPCC method.



3.4 Sensitivity analysis

The LCA findings demonstrated that electricity consumption was the dominant contributor across all environmental impact categories. In the baseline scenario, a 95% reduction in electricity use led to significant decreases in global warming and terrestrial ecotoxicity by 85% and 87%, respectively. Specifically, terrestrial ecotoxicity in the midpoint category declined from 29.5 to 3.6 kg 1,4-DCB, while global warming was reduced from 15.5 to 2.1 kg CO_2-eq. Furthermore, notable reductions were observed in endpoint categories, including resources (from 1.9 to 0.15 USD), human health (from 2.3×10^{-5} to 3.11×10^{-6} DALY), and ecosystem quality (from 5.5×10^{-8} to 7.47×10^{-9} species·yr). These results are consistent with Kaczmarczyk et al. (2024), who reported that lowering electricity consumption and adopting renewable energy in desalination systems can effectively reduce global warming impacts and energy resource demand. Collectively, this evidence highlights the critical importance of replacing fossil fuels with cost-effective renewable energy technologies to preserve environmental integrity and advance sustainability.

4. Conclusion

Identifying environmental hotspots and evaluating strategies for process improvement are critical for the sustainable production of UF membranes. This study employed a LCA approach to model the UF membrane fabrication via the phase inversion method, quantifying the contributions of raw materials and energy consumption to environmental impacts. The modeling results revealed that:

1. The most significant environmental impact in the Recipe midpoint method was related to the terrestrial ecotoxicity of 29.5 kg 1,4-DCB due to the release of copper and zinc metals to the air, bromine to water resources, and cypermethrin to the soil ecosystem. 52% of the environmental impacts in the total impact of the midpoint categories were related to the electrical energy consumption. Quantification of environmental impacts in the Recipe endpoint method showed that the use of natural gas, crude oil, hard coal, and brown coal for energy production had the most environmental impacts on resource depletion, with a value of 1.9 USD.

2. The results of the IPCC modeling confirmed the accuracy of the Recipe method results and showed that the gases emitted from fossil fuels in the energy production stage had the largest contribution to global warming. Making a 95% change in the amount of electrical energy in the sensitivity analysis reduced the impacts of terrestrial ecotoxicity, global warming, and resource depletion approximately by 85%, 73%, and 90%, respectively.

Therefore, to enhance production processes and mitigate adverse environmental impacts during industrial decision-making, it is recommended to apply LCA-based impact assessment, integrating the use of clean energy and minimizing emissions during the manufacturing phase. Such an approach promotes sustainable development and optimizes environmental, economic, and social performance.

Statements and Declarations

Acknowledgement

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Data Availability

The data used (or generated) in this research are presented in the text of the article.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this article.

Author contribution

Z. Salahshour: Modeling, study design, analysis of results, and writing of the paper; A. Shahbazi: Project management, data analysis, and validation; M. Esmaili: experiments and data collection.

AI Use Declaration

This study did not incorporate artificial intelligence techniques; instead, all analyses and optimizations were conducted using conventional and widely accepted analytical methods.

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