Case Report

Lifecycle assessment of membrane synthesis for the application of thermo-osmotic energy conversion process

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ABSTRACT

The thermo-osmotic energy conversion (TOEC) process harnesses low-grade waste heat for electricity generation. Key to TOEC is selecting membrane materials, with polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) being common choices. This study provides the first life cycle assessment (LCA) of PTFE and PVDF membranes, assessing both lab-scale and large-scale production. It identifies key chemical contributors to their environmental impact and cumulative energy demand (CED). PTFE has a lower CED in regions with renewable energy, while PVDF may be viable in areas reliant on non-renewable biomass. These insights can inform decision-makers in strategizing the implementation of TOEC processes for sustainable development.

1. Introduction

In a world with growing energy demands and increasing concerns about climate change, it is essential to use available energy resources wisely [1,2]. At the heart of this challenge lies the need to efficiently capture low-grade waste heat—an abundant and frequently overlooked energy source found in industrial processes, power generation, and many other applications [3–6]. The pursuit of harnessing this otherwise wasted energy has driven innovation and led to the emergence of novel technologies. Among these, the thermo-osmotic energy conversion (TOEC) process is a promising avenue for transforming low-grade waste heat into useable power [7–9]. This innovative technology utilizes the osmotic pressure difference created by temperature gradients, or partial vapor pressure difference, to drive water molecules across a permselective hydrophobic membrane [10–13]. As heat is applied to one side of the membrane, water molecules evaporate from the warmer solution and condense on the cooler side, creating a flow of water molecules through the membrane. This flow of water generates hydraulic pressure, which can be harnessed to drive a turbine or generate electricity directly. By effectively capturing and utilizing low-grade waste heat, TOEC offers a promising solution for increasing energy efficiency and reducing greenhouse gas emissions in various industrial and commercial applications [7,14–16].

While TOEC holds remarkable potential for converting low-grade

heat into electricity, its widespread implementation faces challenges. These challenges revolve around the critical role of membranes in the TOEC process [10,17]. The choice of membrane material is paramount in determining the efficiency, durability, and environmental impact of the entire TOEC system [18–21]. Polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) are two common membrane materials used in the TOEC process. The selection of the appropriate membrane material, whether PVDF or PTFE, is crucial in TOEC system design since it directly influences the system's performance, efficiency, and overall feasibility. The chosen membrane material must exhibit sufficient durability to withstand prolonged exposure to varying temperatures and operating conditions [22,23]. Furthermore, considering the environmental impact of membrane production and disposal is essential to ensure the sustainability of TOEC technology. Therefore, conducting a thorough evaluation of energy and environmental impacts is essential to ensure the informed and careful adoption of these membranes [24].

Currently, there is a lack of systematic assessment regarding the environmental impacts of PTFE and PVDF membrane synthesis. It is essential to assess the cumulative energy demand (CED) and environmental impacts of lab-scale synthesis of these membranes through a life cycle assessment (LCA) approach. LCA provides a holistic framework for evaluating the energy demand and the environmental implications of a product or process throughout its entire life cycle [25–28]. Conducting an LCA on a membrane involves data collection and inventory analysis

to gather information on the energy and material inputs, emissions, and other relevant environmental aspects associated with membrane synthesis. This includes evaluating raw material extraction, manufacturing processes, energy consumption, and waste generation [25,29–31].

Lawler et al. [29] conducted a life cycle assessment model for reverse osmosis membrane manufacturing and explored end-of-life options. They revealed that membrane reuse over one year is more environmentally favorable than landfill disposal, with transportation distance and lifespan significantly influencing reuse viability. In the context of product development, Firouzjaei et al. [25] presented the first lifecycle assessment on the MXene nanomaterials family. They provided an inventory of material, energy, and waste flows for the synthesis of $Ti_3C_2T_x$ MXene and examined the CED and environmental implications of $Ti_3C_2T_x$ synthesis. Factors such as precursor production, selective etching, delamination processes, laboratory location, energy mix, and raw material type were investigated. Their findings revealed that laboratory electricity usage for synthesis processes accounted for over 70 % of the environmental impacts. This study bridges the gap between real-life products and laboratory-scale MXene. LCA studies could aid in the development of new membranes and products tailored to industrial needs.

This pioneering work represents the first-ever LCA study that covers both laboratory-scale synthesis and large-scale production of the crucial TOEC membranes. By meticulously analyzing the entire life cycle, from raw material extraction to end-of-life stages, we gained valuable insights into the total energy requirements and environmental implications of producing PTFE and PVDF membranes.

2. Material and methods

2.1. Membrane fabrication process

The PTFE membrane was prepared using the paste extrusion-stretching method, following a step-by-step procedure. Initially, aqueous polyvinyl alcohol (PVA) solution was meticulously prepared by dissolving PVA powder in distilled water at 90 °C, while ensuring constant agitation for a minimum of 6 hours. A lubricant is added to the PTFE resin to facilitate the extrusion process. The lubricant helps to reduce friction and improve the flow properties of the PTFE resin. The most commonly used lubricant for PTFE membrane fabrication is naphtha. Subsequently, a predetermined amount of aqueous PTFE dispersion was added to the PVA solution, maintaining a PTFE-PVA mass ratio of 4:1. Nonionic surfactants are commonly used to stabilize the PTFE emulsion and prevent coagulation of the particles. During the preparation of the PTFE emulsion, the surfactant is added to ensure proper emulsification. The addition of nonionic surfactants during PTFE membrane fabrication can help control the pore size and morphology of the membrane. The resulting solution, which appeared heterogeneous, was gradually cooled to room temperature. After 3 hours of continuous stirring, the solution underwent a degassing process under vacuum for 8 hours. Next, the solution was cast onto a clean and smooth stainless-steel plate to form films, which were further immersed in pure ethanol to yield PTFE-PVA composite films. These films were air-dried and subsequently sintered in a muffle furnace at 360 °C for 3 minutes. The sintering process caused the PVA matrix to decompose, resulting in the formation of interconnected pores within the PTFE membrane. To conduct a detailed analysis of PTFE membrane fabrication on a small scale, we employed the following formulation: 60 g of PTFE, 15 g of PVA, 5 g of naphtha, 45 g of deionized water, 5 g of a nonionic surfactant, and 10 g of ethanol. This combination yielded a PTFE membrane with a surface area of 1430 cm^2.

The PVDF membrane was prepared using the phase inversion process, following a detailed procedure. Initially, the dope solution was created by blending LiCl (5 wt%) to enhance the coagulation rate, SiO_2 (2 wt%) as well as dimethylacetamide (DMAc) (81 %) as the solvent. PVDF (12 wt%) was then introduced into the dope solution and stirred at 300 rpm at 60 °C for 24 hours, ensuring complete dissolution and homogeneous solution. Hydrophobic SiO_2 nanoparticles were incorporated into the PVDF precursor solution to increase hydrophobicity and, thus, liquid entry pressure, which is essential for the TOEC process. Research studies have also shown that adding hydrophobic SiO2 increases porosity, resulting in an elevated permeate flux [32]. The polymer solution was subsequently degassed in a vacuum oven at room temperature for 4 hours. The dry-wet phase inversion process was employed to manufacture the flat sheet membrane. Initially, a piece of polyester support was affixed to a glass plate. The polymer solution was then cast onto a nonwoven fabric using a 0.15-μm casting knife. After being exposed to air for 15 seconds, the film was immersed in a DI water bath at 25 °C, allowing for phase inversion to occur. Once the phase inversion was complete, the solidified polymer sheet was carefully detached from the plate and soaked in deionized water at ambient temperature for 24 hours. Subsequently, it was soaked in ethanol and n-Hexane for 15 minutes each, respectively, to minimize shrinkage effects by gradually reducing surface tension during the drying process. Finally, the membrane was dried for 24 hours at room temperature. To fabricate a 280 cm^2 PVDF membrane for our small-scale analysis, we considered the combination of the following materials: 2.4 g of PVDF, 16.2 g of DMAc, a 320 cm^2 polyester substrate, 100 g of DI water, 1 g of LiCl, 0.4 g of SiO_2, 1.5 g of ethanol, and 1.5 g of n-hexane.

2.2. Lifecycle assessment methodology

For the small-scale assessment, we considered lab-scale fabrication of 1430 cm^2 of PTFE and 280 cm^2 of PVDF membrane. We assessed the CED and environmental impacts of lab-scale synthesis of the membranes, considering resource utilization, chemical emissions, and stressor potency, utilizing the underlying techniques in TRACI. The models and data employed for each impact category ensure accuracy in evaluating potency. For certain impact categories, such as ozone depletion and global warming effects, an international agreement exists on the relative potency of the chemicals listed. However, for other impact categories, relative potency is determined based on chemical and physical principles or experimental data models [25].

Moving on to the large-scale assessment, our focus was on generating power for 2000 people over a period of 10 days. Considering a daily power consumption of 25 kWh per person, we aimed to generate a total of 500,000 kWh of energy. The power density values obtained from our modeling on the TOEC process were 2.986 W/m^2 for PVDF and 4.290 W/m^2 for PTFE membrane [7]. Based on our calculations, the required membrane area for generating large-scale power by the TOEC process was found to be approximately 697,700.38 m^2 of PVDF membrane and 485,625.49 m^2 of PTFE membrane. It's noteworthy that achieving such a vast surface area necessitates the utilization of 65,000 to 80,000 TOEC 4040 spiral-wound elements. This is a significant quantity, especially when compared to the standard industrial-scale reverse osmosis (RO) plants, which typically employ between 2000 and 16,000 elements. This comparison draws upon the operational models of renowned facilities like the Sorek and Hadera Desalination Plants in Israel, the Carlsbad and Tampa Bay Seawater Desalination Plants in the USA, and the Fujairah 1 plant in the UAE.

These figures highlight the current limitations of TOEC membrane technology, particularly in terms of power density. To realize the full potential of this technology on a larger scale, further enhancements in power density are imperative. This insight indicates the ongoing quest for innovation and optimization within the field of desalination technology.

3. Results and discussion

3.1. Small-scale assessment

3.1.1. Cumulative energy demand (CED) of PTFE and PVDF membrane synthesis

The CED values represent the total energy consumption included throughout the entire production lifecycle of a product. CED considers energy from various sources, including both non-renewable (e.g., fossil fuels) and renewable (e.g., solar, wind, hydro) sources [25,33]. Fig. 1 shows the CED values attributed to the small-scale manufacturing process of PTFE and PVDF membranes. The data have been normalized by considering the production of 1430 cm^2 for both membranes. In both membranes, fossil fuel and renewable biomass sources stand out as the primary contributors to the CED, while other energy sources, such as non-renewable biomass, nuclear, water, wind, solar, and geothermal, have a negligible impact on the CED. This heavy reliance on fossil sources raises concerns from both environmental and resource availability perspectives. The high proportion of fossil fuel energy in the CED of these membranes suggests a considerable carbon footprint associated with their production. This highlights the urgency of exploring alternative, more sustainable energy options for membrane production, such as greater integration of renewable energy sources like wind, solar, and geothermal, which currently make up only a minor fraction of the CED. Such efforts are crucial for mitigating environmental impacts and enhancing the sustainability profile of membrane production processes.

Fig. 2 provides a detailed breakdown of the chemical contributions to the CED of PTFE and PVDF membranes for various energy sources. The analysis reveals distinct patterns in the chemical impacts on the CED for different energy inputs, shedding light on areas for potential improvement in energy efficiency and sustainability.

In the case of PTFE membrane, the synthesis process is notably influenced by PTFE resin, which emerges as the most significant contributor to the fossil-based CED, constituting 44.5 % of the total fossil CED. Additionally, DMAc and electricity play pivotal roles in the fossil-based CED of PVDF membrane synthesis, with contributions of 43.9 % and 27.5 %, respectively.

When considering non-renewable biomass sources, polyvinyl alcohol emerges as the primary contributor to the CED of the PTFE membrane, while ethanol plays a key role in the CED of the PVDF membrane. Nuclear energy sources primarily affect the CED of PTFE membranes through the usage of PTFE resin, which accounts for 71.2 % of the corresponding CED. On the other hand, PVDF powder and DMAc significantly contribute to the CED of nuclear-based energy sources for PVDF membrane synthesis, contributing 40.5 % and 34.5 %, respectively.
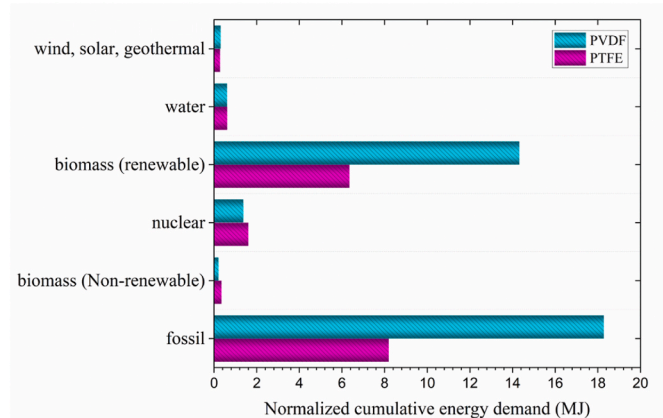
In the case of water energy sources, PTFE resin plays a crucial role, contributing to 67.6 % of the CED of PTFE membrane, and for the case of PVDF membrane, DMAc, electricity, and PVDF powder are the dominant contributors. As for wind, solar, and geothermal sources, the contributions of PTFE resin and electricity are higher than the rest of the chemicals, amounting to 48.9 % and 28.9 %, respectively, and for the case of PVDF membrane, electricity emerges as the primary contributor, making up 54.7 % of the CED of the membrane synthesis.

Overall, these findings underscore the significant variations in chemical impacts on the CED across different energy sources, with PTFE resin often being the primary contributor to CED of PTFE membrane and the substantial impact of DMAc, electricity, and ethanol on the CED of the PVDF membrane. Given that PTFE resin is an indispensable component for fabricating PTFE membrane, and it cannot be substituted with another chemical, it is recommended to explore alternatives for the chemicals that have significant energy demands. This approach can help reduce the CED associated with the production process of the PTFE membrane. On the other hand, it is important to explore alternative solvents or methodologies that reduce the reliance of PVDF membrane fabrication on DMAc, which is a chemical with a significant energy footprint. Developing more energy-efficient methods of electricity generation and utilization in the synthesis process is also crucial to decreasing the energy demand associated with PVDF membrane production.

3.1.2. Environmental impacts of PTFE and PVDF membrane synthesis

Fig. 3 provides a detailed overview of the environmental impacts associated with the synthesis of PTFE and PVDF membranes, highlighting the contributions of each chemical to various impact categories.

For PTFE membrane synthesis, PTFE resin emerges as the primary contributor across all impact categories, except for eutrophication, where electricity takes precedence. This underscores the significant environmental footprint of PTFE resin in the manufacturing process. Moreover, nonionic surfactants and electricity also contribute substantially to environmental impacts. To address these concerns, it is advisable to explore greener alternatives for nonionic surfactants and implement measures to reduce electricity consumption. This could involve adopting energy-efficient equipment, optimizing manufacturing processes to minimize synthesis time, and exploring renewable or cleaner sources of electricity. By implementing these strategies, the environmental impact of PTFE membrane synthesis can be significantly reduced, enhancing overall sustainability.

In contrast, for PVDF membrane synthesis, DMAc, and electricity consistently rank as the primary contributors across most impact categories. This highlights the significant environmental footprint associated with the usage of DMAc in the manufacturing process. To mitigate these impacts, efforts should be made to reduce energy consumption in electrical equipment and shorten synthesis times. Additionally, exploring alternative substitutes for DMAc could help alleviate the environmental footprint of PVDF membrane synthesis. Investing in research and development of alternative solvents or methodologies can improve the environmental sustainability of PVDF membrane production.

To address the environmental impacts of membrane synthesis and production, several strategies can be implemented. One effective approach is the adoption of renewable energy sources. By increasing the proportion of renewable energy used in production processes, the global warming potential and other impacts associated with fossil fuel can be significantly reduced. Transitioning to solar, wind, or hydroelectric power not only decreases the carbon footprint but also aligns with global sustainability goals. Another key strategy is the development of green chemistry alternatives. Researching and utilizing alternative, less harmful chemicals and solvents can help reduce the toxicity and overall environmental footprint of membrane synthesis. By replacing high-impact solvents like DMAc with greener options, the production process can become safer and more sustainable. Implementing robust waste
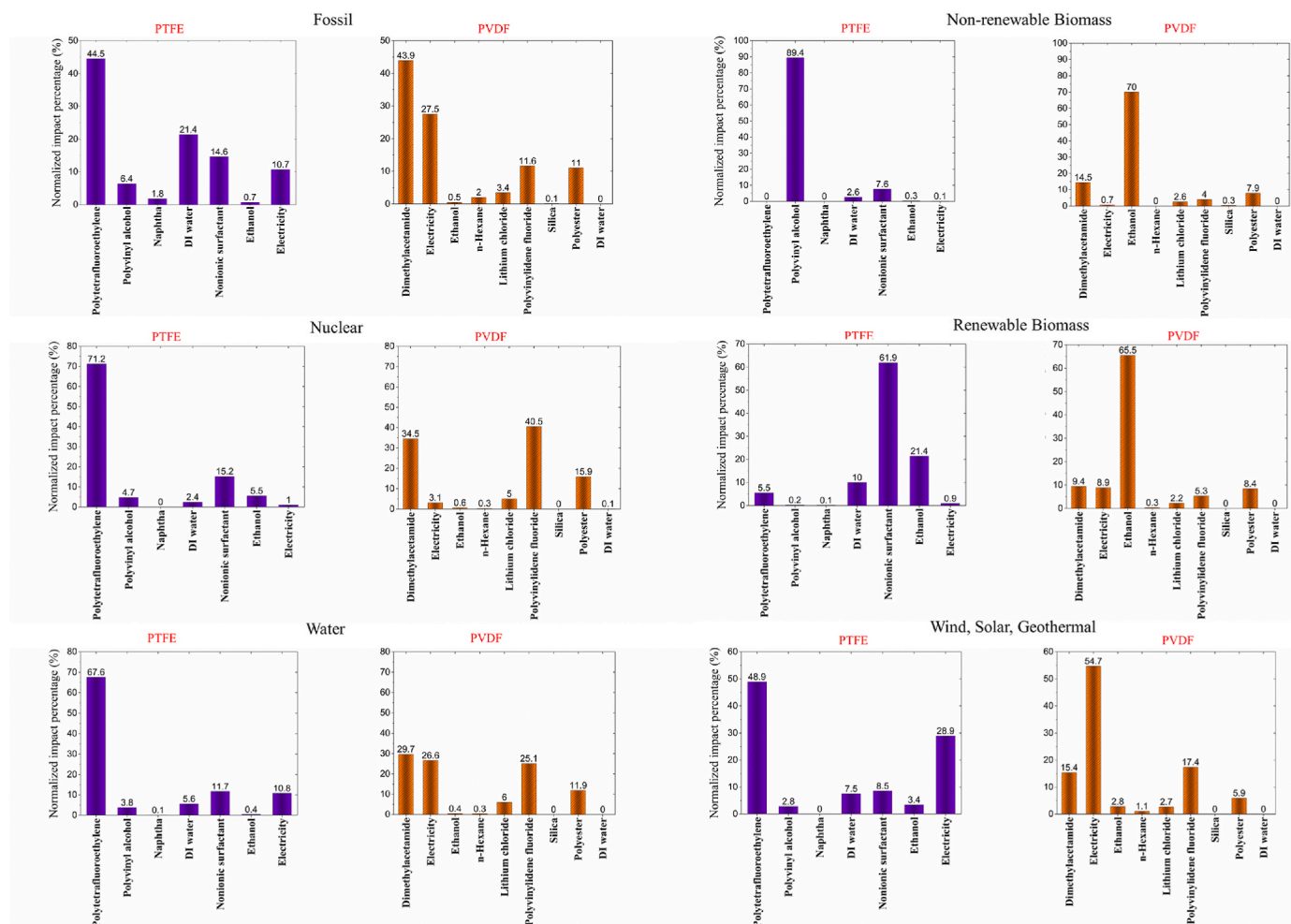

Fig. 1. Cumulative energy demand (CED) associated with the lab-scale production of PTFE and PVDF membranes.

Fig. 2. Contribution of each chemical to the energy demand of PTFE membrane synthesis for various energy sources.

management and recycling strategies for end-of-life membranes is essential for mitigating the environmental impacts associated with disposal. Developing methods for closed-loop recycling processes and investigating the potential for repurposing used membranes in different applications can minimize waste generation, reduce the need for virgin materials, and extend the lifecycle of membrane products.

Overall, the analysis presented in Fig. 3 shows the importance of identifying and addressing the critical contributors to environmental impacts in membrane synthesis processes. By implementing targeted strategies such as exploring alternative chemicals, reducing energy consumption, and optimizing manufacturing processes, the ecological sustainability of both PTFE and PVDF membrane production can be enhanced, contributing to overall environmental conservation efforts.

3.2. Large scale assessment

In the large-scale assessment, we analyze the CED and environmental impacts associated with the production of PTFE and PVDF membranes when scaled up for energy generation using the TOEC process. This section aims to provide a comprehensive overview of the energy consumption and environmental footprint of producing these membranes at a scale sufficient to generate electricity for a significant population. For large-scale applications, our analysis considered generating power for 2000 people over a period of 10 days, requiring a total energy of 500,000 kWh. Fig. 4(A) presents the analysis of PTFE and PVDF membranes concerning CED from various energy sources. The data reveals that, with the exception of non-renewable biomass sources, PVDF

membranes exhibit a higher energy demand in all energy sources. High energy demand not only impacts operational costs but also intensifies the carbon footprint and reliance on finite energy resources, particularly in cases where non-renewable sources are used. As industries continue to prioritize energy efficiency and environmental sustainability, the greater energy demand for PVDF membranes calls for careful consideration when choosing the appropriate membrane material for specific processes. Fig. 4(B) details the environmental impacts across various categories, showing PVDF membranes generally exhibit a greater environmental footprint than PTFE membranes, except in global warming and ozone depletion impacts, with key environmental categories including eutrophication, acidification, and photochemical smog formation. The environmental impacts of PTFE membrane synthesis are primarily driven by PTFE resin, while DMAc and electricity are the major contributors for PVDF membranes, with nonionic surfactants also playing a significant role for PTFE.

To reduce these impacts, it is recommended to explore greener alternatives for nonionic surfactants and improve energy efficiency in manufacturing processes. The analysis shows that achieving the required membrane area for TOEC processes is a challenge due to the current power density limitations. Renowned RO plants such as the Sorek and Hadera Desalination Plants in Israel and the Carlsbad and Tampa Bay Seawater Desalination Plants in the USA use far fewer elements, highlighting the need for further innovations in membrane technology to improve power density and make TOEC processes more feasible on a large scale.
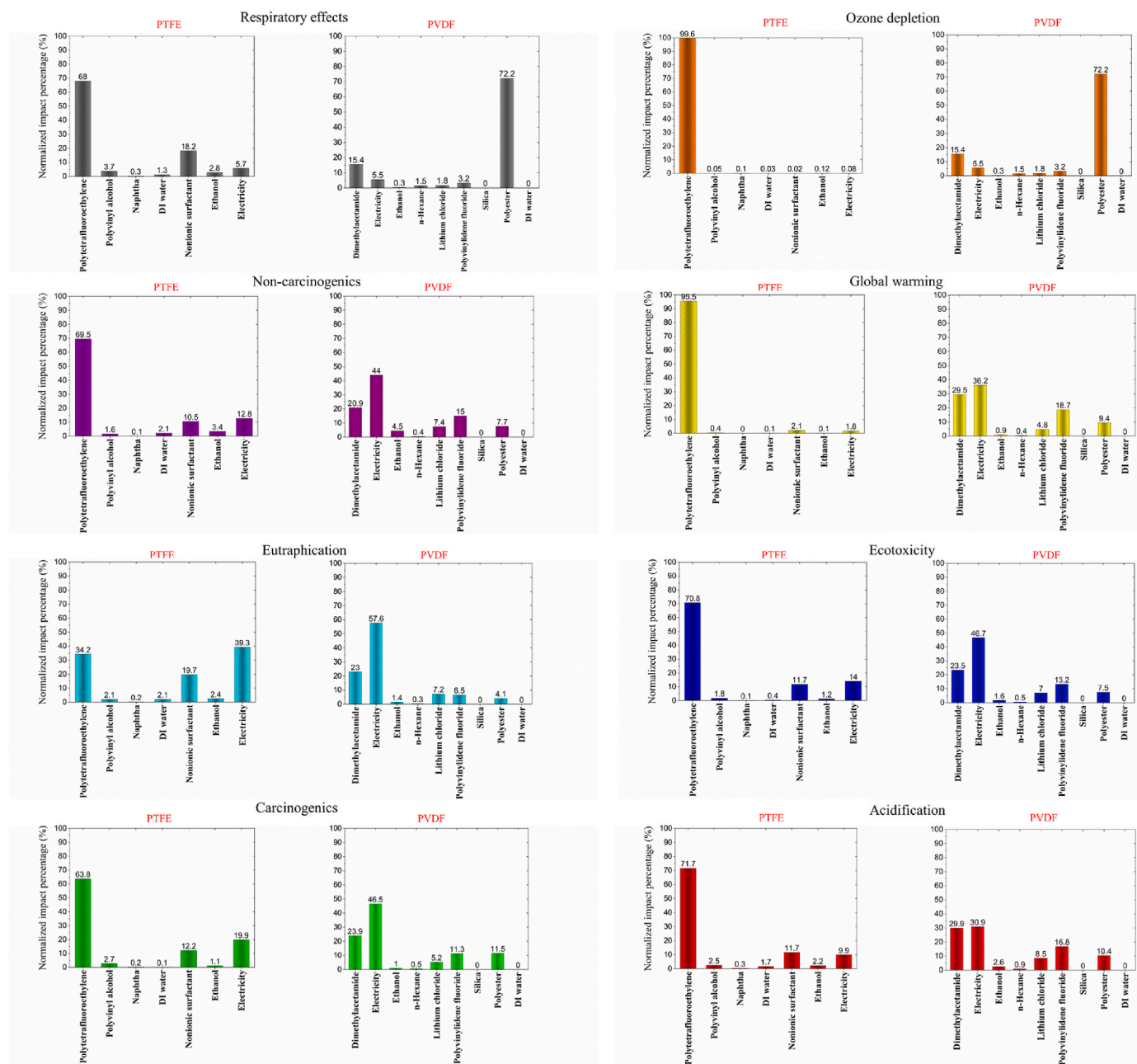
Fig. 3. Contribution of each chemical to the environmental impacts of synthesis of PTFE and PVDF membrane.

3.3. Potential future directions of research

Future research in the field of membrane technology can significantly benefit from several promising directions. One critical area is the development of green membrane materials. Research should focus on creating new membrane materials with a lower environmental impact compared to traditional materials like PTFE and PVDF. This involves investigating bio-based polymers and other sustainable materials that can deliver similar or superior performance in TOEC processes. The expected outcomes include a reduced carbon footprint, lower energy consumption during synthesis, and enhanced biodegradability of the membranes.

Another important direction is the optimization of membrane fabrication processes. Improving the efficiency and sustainability of these production techniques can lead to significant environmental benefits. Researchers should aim to develop and implement energy-efficient synthesis methods, such as solvent-free techniques or low-energy phase inversion processes. This approach can result in a lower CED and reduced emissions, promoting more sustainable production practices. The exploration of alternative solvents is also crucial for advancing membrane technology. By replacing high-impact solvents like DMAc with greener alternatives, researchers can mitigate the environmental and health impacts associated with solvent use in membrane synthesis. Identifying and testing solvents that are less toxic and more sustainable can lead to safer and more environmentally friendly production processes.

Integrating renewable energy sources into membrane manufacturing processes can further reduce the environmental footprint. Transitioning production facilities to utilize solar, wind, or hydroelectric power, along with developing energy storage solutions for continuous operation, can significantly cut the carbon footprint of membrane production and align it with global sustainability goals.

Advanced surface modification techniques offer promising opportunities to improve the antifouling properties and overall performance
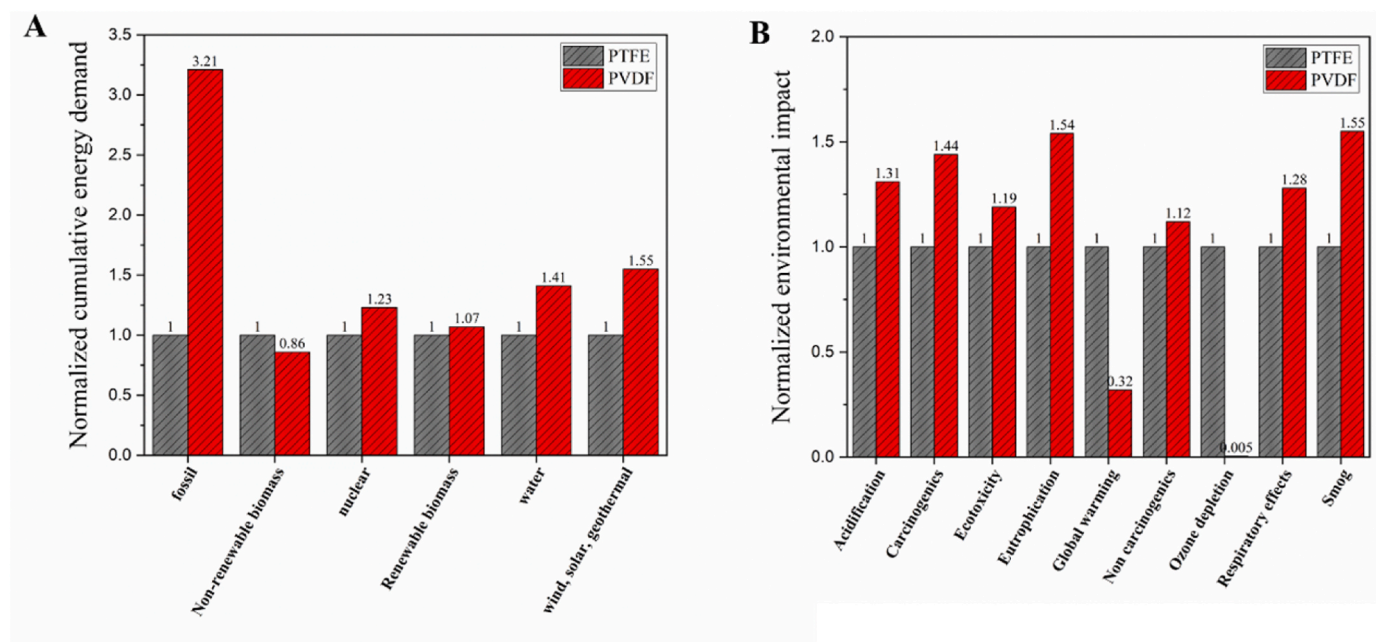
Fig. 4. Large-scale evaluation of PTFE and PVDF membrane fabrication. (A) Comparative analysis based on CED from various energy sources. (B) Comparative assessment across multiple environmental impact categories.

of membranes. Researching techniques such as plasma treatment, grafting hydrophilic or antimicrobial polymers, and embedding nanoparticles can enhance membrane durability, reduce fouling, and extend operational lifespans, ultimately lowering maintenance costs and improving efficiency.

4. Conclusion

In conclusion, the comprehensive assessment of CED and environmental impacts sheds light on critical insights for enhancing the sustainability of PTFE and PVDF membrane synthesis processes. The analysis demonstrates the heavy reliance on fossil fuels in membrane production, highlighting the urgent need for greater integration of renewable energy sources to mitigate environmental impacts and reduce carbon footprints. Furthermore, the breakdown of chemical contributions to the CED reveals significant variations across different energy sources, with PTFE resin often emerging as the primary contributor to the CED of PTFE membranes. In contrast, chemicals like DMAc, electricity, and ethanol play substantial roles in the CED of PVDF membranes. These findings emphasize the importance of exploring alternatives for chemicals with significant energy demands to minimize overall CED. Environmental impact assessments reveal that electricity dominates most impact categories for both membrane types. Suggestions for reducing environmental footprints include substituting nonionic surfactants with greener alternatives for PTFE membrane fabrication and exploring energy-efficient equipment and alternative solvents to decrease the reliance on DMAc in PVDF membrane production. These findings provide valuable insights for policymakers, researchers, and industry stakeholders to prioritize sustainable practices and innovation in membrane manufacturing processes. By implementing recommended strategies such as greater reliance on renewable energy sources, adopting energy-efficient technologies, and exploring alternative chemicals, the membrane industry can move towards a more environmentally friendly and sustainable future.

CRediT authorship contribution statement

Kazem Moradi: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Mostafa Dadashi Firouzjaei: Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mark Elliott:** Writing – review & editing, Supervision, Resources, Formal analysis, Conceptualization. **Mohtada Sadrzadeh:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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