Exergetic analysis on membrane separation processes: an overview.

Giovanni Souza Casella [a].

[a] Department of Sanitary and Environmental Engineering, School of Engineering, Federal University of Minas Gerais, Av. Antônio Carlos 6627, Pampulha, Belo Horizonte-MG, 31270-901, Brazil.

Abstract. Bibliometric analysis is an important tool for understanding and filtering the main articles from some specific field of research. In this work, the "bibliometrix" package (R language) was used to overview the state-of-the-art of exergetic analysis applied to the membrane separation process. For the research, it was applied the expressions: 'Membrane AND "exergetic analysis"', both refined by Topic (TS) and by year from 2019 to 2024. Data were collected from Science Citation Index Expanded (SCI-E) - Clarivate Analytics' ISI - Web of Science©. The bibliometric search performed returned a total of 12 documents, of which 9 are research articles and 3 are reviews. However, some of the documents do not fit the scope of this research, indicating some space for optimization in the search. Through the articles, it was possible to notice that the exergy analyses are mainly done by simulation. Most of the works considered exergy as the sum of the thermal, and chemical exergy. This is important to make it possible to do any comparison among different research. However, because of the variety of usage of the membrane process, comparing the exergy analysis reported in the articles is almost impossible. It indicates that more studies on exergy analysis should be done, in order to increase the number of publications and to become possible to restrict the analysis to some specific process. Related to the scientific collaboration, the bibliometric analysis showed that research is being done without great exchange among the different research groups. It is important to highlight this result since science is a collaborative work, and it is expected that linkage among different research groups will be made when this specific topic becomes more mature.

Keywords. Membrane separation, Exergetic analysis, Thermodynamics' second law, Bibliometric analysis.

1. Introduction

Because membrane technology performs better than conventional separation technology, it has caught the interest of separation technology researchers. Due to its greater technological and financial viability, it has been specifically — though not exclusively — used for the water treatment process since the 1990s [1,2].

Membrane separation is a process that uses a semipermeable barrier (membrane) to partially separate a feed that contains a mixture of two or more components. A membrane is a thin layer of material, either manufactured or natural, that covers a surface and is permeable to some components of the solution [2].

Membranes are commonly classified by their pore openings, membrane distillation (MD), microfiltration (0.1–1.0 μm) (MF), ultrafiltration (10–1000 Å) (UF), nanofiltration (0.5–1 nm) (NF), reverse osmosis (1–10 Å) (RO). All membrane classifications use pressure difference as their driving force, with the exception of membrane distillation (MD), which is caused by the vapor pressure gradient created by temperature difference [1].

Although the extensive use of membranes for water recovery through wastewater treatment, their sustainability must be deeply studied from a more holistic point of view. Exergetic analysis is a sustainable tool that can be used to evaluate the performance of membrane operations in terms of efficient use of energy, and resources, aside from showing points of loss of energy and being capable of optimizing a particular process [3,4].

The second law of thermodynamics deals with the quality of energy, while the first law deals with the quantity of energy and states that energy cannot be created or destroyed. To be more precise, the second law of thermodynamics states that energy has both quality and quantity. The first law of thermodynamics only considers the quantity of energy and ignores its quality. Quality is defined as an energy source's capacity to produce a certain quantity of change, its work potential, or the amount of energy that can be converted into meaningful work or exergy. For this reason, exergy analysis is a useful substitute for traditional energy analysis. It can be used to find significant efficiencies and thermodynamic losses in a process as a whole as well as its steps [5,6].

The concepts of exergy, available energy, and availability are essentially similar. The concepts of exergy destruction, exergy consumption, irreversibility, and lost work are also essentially similar. Exergy is also a measure of the maximum useful work that can be done by a system interacting with an environment that is at a constant pressure P0 and a temperature T0 [5].

This work aimed to give an overview of the state-of-the-art scientific literature related to membrane separation processes and exergy analysis focused on understanding how this sustainable methodology is used in this particular process.

2. Research Methods

2.1 Literature search

A bibliometric analysis was performed using the "bibliometrix" package (R language) [7]. Data were collected from Science Citation Index Expanded (SCI-E) - Clarivate Analytics' ISI - Web of Science©.

For the research, it was applied the expressions: 'Membrane AND "exergetic analysis" ', both refined by Topic (TS). The publications were also limited by publication year, from 2019 to 2024.

All graphical and statistical analyses performed using this dataset were obtained from the "bibliometrix" package (R language).

3. Results and discussion

The bibliometric search performed returned a total of 12 documents, of which 9 are research articles and 3 are reviews. Fig. 1 shows the temporary distribution of those documents. It is possible to notice that the number of new publications on the topic increases every year, showing the increasing interest of the scientific community in exergetic analysis applied to the membrane separation process.

3.1 Documents analysis

Although the document sample is short, classifying the document by the most cited is an important way to understand the most influential and studied topics in this field of research [8]. Table 1 shows the works sorted by their total citation and normalized total citations.

Tab. 1 – Found articles sorted by total citations.

Reference	Total Citations	Normalized Total Citations
[9]	31	1,90
[10]	30	1,00
[14]	12	0,73
[13]	10	1,88
[15]	9	1,69
[4]	7	1,31
[16]	6	0,37
[3]	4	0,75
[17]	4	2,00
[11]	1	0,19
[18]	1	0,19
[12]	0	0,00

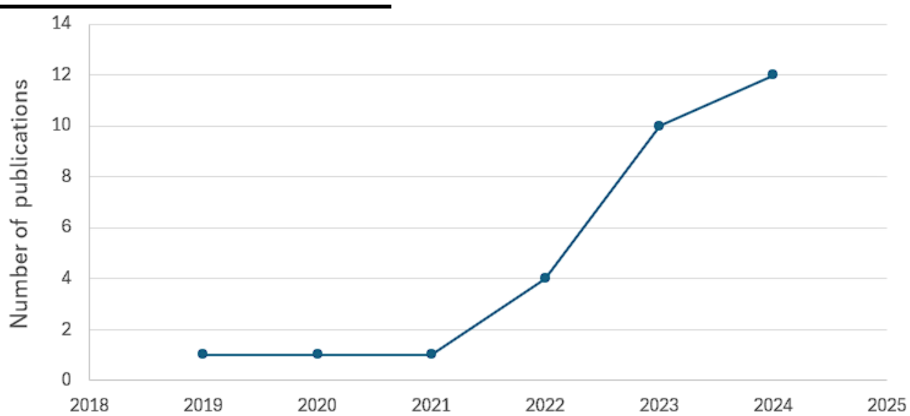

Fig. 1 – Total articles' production by year.

Besides the usage of the search expressions previously presented, some of the documents do not fit the scope of this research, such as [9-11]. Also, the review articles [3,12,13], were not considered for the analysis.

Through the remaining articles, most of the articles worked with simulated systems, excluding Zaheer *et al.* [18] which is worked on a laboratory membrane distillation unit. Qin *et al.* [14] simulated a new hybrid system model consisting of a high-temperature proton exchange membrane fuel cell and a direct contact membrane distillation, aiming at both electricity and freshwater cogeneration. The authors segregated exergetic efficiency and destruction for the isolated processes and the hybrid system.

It was evaluated the influence of the feed and permeate water temperature, flow velocities of both feed water and permeate water, convective heat transfer coefficients of the feed side and permeate side, and the porosity and thickness of the hydrophobic membrane. Almost all variables showed a positive effect on the hybrid system's performance. Hydrophobic membrane thickness and permeate water temperature were the only ones that showed negative effects on the system's performance. The proposal system presented an exergic efficiency of 23.3 %, which is, 112.0 % greater than that of a single fuel cell system. Simultaneously, the exergy destruction rate decreased by 28.1 %.

A novel residential combined cooling, heating, and power system, consisting of a biomass gasifier, a proton exchange membrane fuel cell stack, an absorption chiller, and auxiliary equipment, was proposed by Yang *et al.* [15]. Exergy was calculated considering the sum of the thermochemical exergy and the chemical exergy, assuming, also ideal gas. For the exergy analysis, it was possible to notice that exergy destruction distribution was concentrated on biomass gasifier and PEMFC stack. By this result, it is possible to assume that those processes must go towards optimization and/or transformation.

Wang *et al.* [4] proposed a novel integrated process of electrodialysis metathesis - reverse osmosis - mechanical vapor recompression to produce K_2SO_4 from Na_2SO_4. Exergy was calculated considering the sum of the thermal, and electrical exergy inputs to the system, as the term of generations of exergy. The exergy efficiency was presented for each process separately, while electrodialysis reached 82.2 % and reverse osmosis reached 46.0-46.5 %, the system had its efficiency limited by vapor recompression, with 1.1-2.6 %, % due to the large exergy loss of the evaporation process. Once again the exergetic analysis can indicate the steps in the process that need greater improvement.

Qin *et al.* [16] proposed a novel hybrid system with a high-temperature proton exchange membrane fuel cell coupled to a duplex thermoelectric cooler, in order to harvest the waste heat from exothermic reaction processes. The authors investigated the influence of temperature, inlet relative humidity, doping level, current density, electrolyte thickness, and Thomson coefficient on the system performance. The hybrid system's maximum exergetic efficiency was 27.3 %, which is 16.7 % larger than that of the single HT-PEMFC system. Simultaneously, the exergy destruction rate decreased by decreased by 7.7 %.

Taheri *et al.* [17] evaluated a multigeneration system for generating power and hydrogen, using a combined gasification gas turbine cycle, double flash geothermal cycle, and proton exchange membrane (PEM) cycle. Exergy was calculated considering the sum of the thermal and chemical exergy. Although the author has verified the exergy efficiency of each sub-system, the parametric analysis was made just in terms of the multi-generation system. For this reason, verifying the individual aspects of exergy efficiency on the PEM cycle was impossible. Using multi-objective optimization, the exergy efficiency of the optimal point of the system was 29.8 %.

Lastly, Zaheer *et al.* [18] performed an exergy analysis of a laboratory membrane distillation unit working with brines from reverse osmosis (RO). The membranes used in the work were PVDF hollow fiber membranes, exergy was calculated considering the sum of the thermochemical exergy based on the temperature of the streams and the chemical exergy from the solute components in the stream. The exergetic efficiency of the permeate was found to be higher at lower feed temperatures, according to the author it is due to the lower accumulation of concentration polarization along the membrane wall.

Through those articles, it was possible to notice that the exergy analyses are mainly done by simulation. This is due to the simplicity of measuring important variables for its calculation, although laboratory research is possible, as presented by Zaheer *et al.* [18]. Most of the works considered exergy as the sum of the thermal, and chemical exergy. This is important to make it possible to do any comparison among the research.

The analyzed works vary among the usage of the membrane process, showing its already-known versatility. Besides that, comparing exergy analysis from such different usages is impossible. It indicates that more studies on exergy analysis should be done, in order to increase the number of publications and to become possible to restrict the analysis to some specific process.

A three-field graph, Fig. 2, was plotted and the top 10 authors, keywords, and journals were associated. The keywords most frequently used were “desalination”, “exergetic analysis”, and “energetic analysis”. It was somehow expected since exergy and energy are closely correlated and present one of many uses of membrane separation processes. The three more productive authors (Kumar S, Qin Y, and Zhang HC) are strongly connected with the most used keywords.

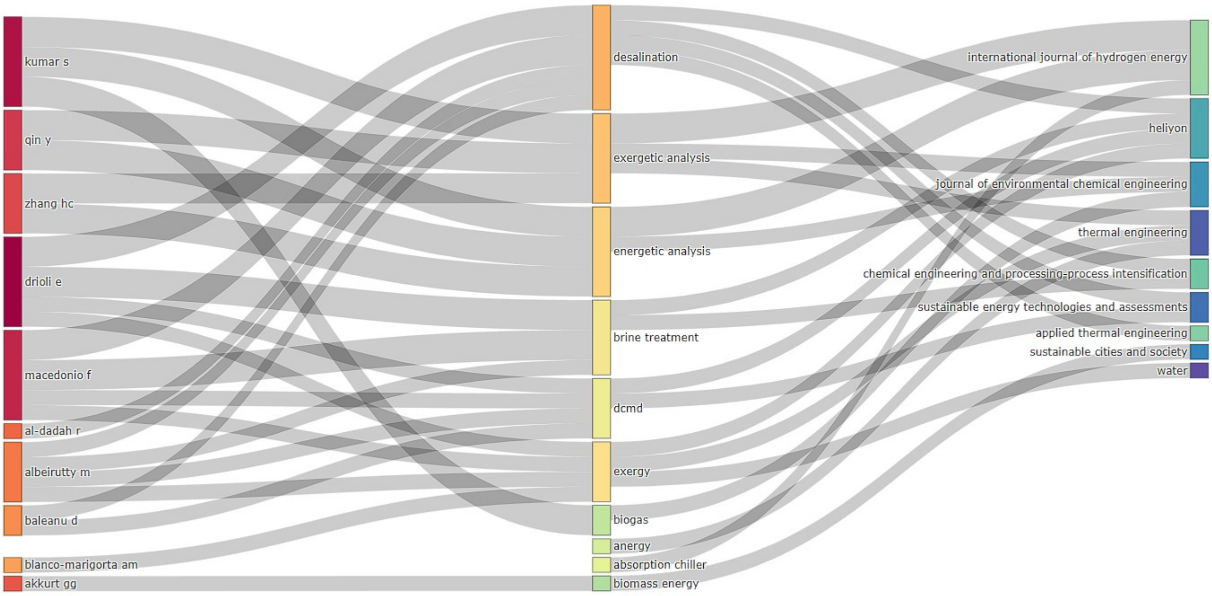

Fig. 2 - Three-field graph: top 10 authors, keywords, and journals.

On the other hand, "desalination" is not correlated with the journal that covers most of the publications, the International Journal of Hydrogen Energy. The three journals that cover most of the publications (International Journal of Hydrogen Energy, Heliyon, and Journal of Environmental Chemical Engineering) have different scopes for their publication. However energetical optimization (either for energy generation or for environmental discussion) is a common aspect that could justify their position on this analysis.

3.2 Scientific interaction

Related to the scientific collaboration, Fig. 3 shows that those researches are being done without great exchange among the different research groups, for the articles analyzed. It can be confirmed for the absence of linkage among the author's names in different groups. It is important to highlight this result since science is a collaborative work, and it is expected that linkage among different research groups will be made when this specific topic becomes more mature.

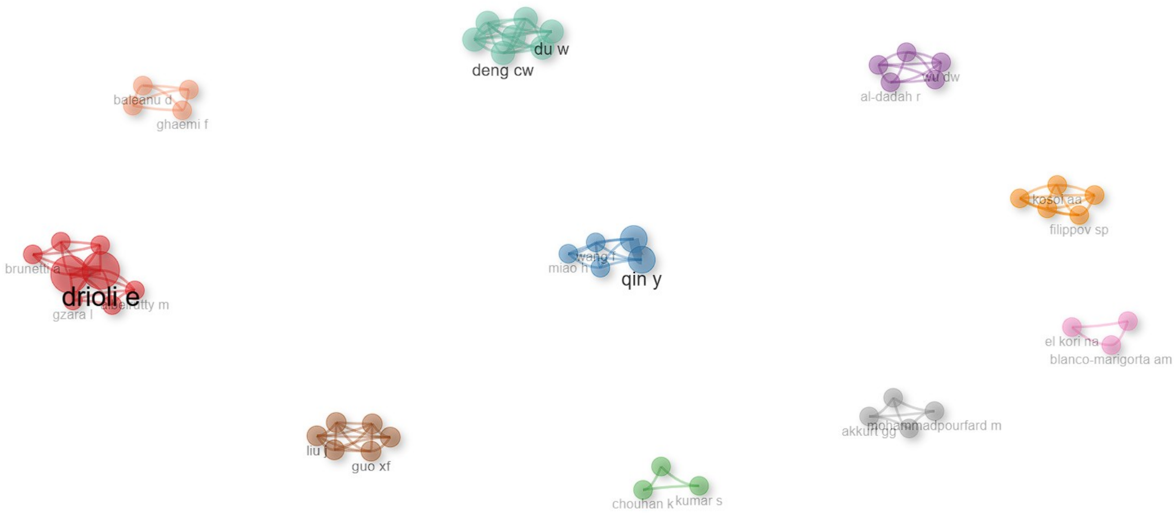

Fig. 3 – Clustering of authors.

4. Conclusion

A bibliometric analysis is an important tool for understanding and filtering the main articles from some specific field of research. In this work, the "bibliometrix" package (R language) was used to overview the state-of-the-art of exergetic analysis applied to the membrane separation process.

The bibliometric search performed returned a total of 12 documents, of which 9 are research articles and 3 are review Although, some of the documents do not fit the scope of this research, indicating some space for optimization in the search.

Through the articles, it was possible to notice that the exergy analyses are mainly done by simulation. This is due to the difficulty in measuring important variables for its calculation in laboratory research. Most of the works considered exergy as the sum of the thermal, and chemical exergy. This is important to make it possible to do any comparison among the research. However, because of the variety of usage of the membrane process, comparing the exergy analysis reported in the articles is almost impossible. It indicates that more studies on exergy analysis should be done, in order to increase the number of publications and to become possible to restrict the analysis to some specific process.

The three-field graph was plotted and authors, keywords, and journals were associated. The keywords most frequently used were "desalination", "exergetic analysis", and "energetic analysis" which are closely related to the three more productive authors (Kumar S, Qin Y, and Zhang HC). On the other hand, "desalination" is not correlated with the journal that covers most of the publications, the International Journal of Hydrogen Energy.

Related to the scientific collaboration, the bibliometric analysis showed that research is being done without great exchange among the different research groups.

5. Acknowledgement

The author expresses his sincere gratitude to the INCBAC Institute - UNIGOU Scientific Training Program for the helpful information and insights given on its course, obtained during this research.

6. References

[1] Wee SL, Tye CT, Bhatia S. Membrane separation process—Pervaporation through zeolite membrane. *Sep Purif Technol*. 2008 Nov;63(3):500–16.

[2] Ravichandran SR, Venkatachalam CD, Sengottian M, Sekar S, Subramaniam Ramasamy BS, Narayanan M, et al. A review on fabrication, characterization of membrane and the influence of various parameters on contaminant separation process. *Chemosphere*. 2022 Nov;306:135629.

[3] Criscuoli A, Macedonio F, Brunetti A, Tocci E, Drioli E. Impact of membrane engineering on the process engineering progresses: Towards a sustainable development. *Chemical Engineering and Processing - Process Intensification*. 2023 Jul;189:109385.

[4] Wang X, Liu J, Ji Z, Zhao Y, Li F, Guo X, et al. Cost and exergy analysis on integrated process of electrodialysis metathesis - reverse osmosis - evaporation for producing K2SO4 from Na2SO4. *Desalination*. 2023 Mar;550:116384.

[5] Hepbasli A. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. *Renewable and Sustainable Energy Reviews*. 2008 Apr;12(3):593–661.

[6] Abuşoğlu A, Özahi E, Kutlar Aİ, Demir S. Exergy analyses of green hydrogen production methods from biogas-based electricity and sewage sludge. *Int J Hydrogen Energy*. 2017 Apr;42(16):10986–96.

[7] Aria M, Cuccurullo C. bibliometrix : An R-tool for comprehensive science mapping analysis. *J Informetr*. 2017 Nov;11(4):959–75.

[8] Sillero L, Sganzerla WG, Forster-Carneiro T, Solera R, Perez M. A bibliometric analysis of the hydrogen production from dark fermentation. *Int J Hydrogen Energy*. 2022 Jul;47(64):27397–420.

[9] Tlili I, Mohammad Sajadi S, Baleanu D, Ghaemi F. Flat sheet direct contact membrane distillation study to decrease the energy demand for solar desalination purposes. *Sustainable Energy Technologies and Assessments*. 2022 Aug;52:102100.

[10] Chouhan K, Sinha S, Kumar S, Kumar S. Utilization of biogas from different substrates for SOFC feed via steam reforming: Thermodynamic and exergy analyses. *J Environ Chem Eng*. 2019 Apr;7(2):103018.

[11] Kosoi AS, Kosoi AA, Popel' OS, Zeigarnik YuA, Sinkevich M V., Filippov SP. An Exergetic Analysis of New Thermodynamic Cycles Involving Carbon Dioxide Capture. *Thermal Engineering*. 2023 Jul 4;70(7):496–516.

[12] Arakcheeva El Kori N, Blanco-Marigorta AM, Melián Martel N. Definition of Exergetic Efficiency in the Main and Emerging Thermal Desalination Technologies: A Proposal. *Water (Basel)*. 2024 Apr 27;16(9):1254.

[13] Farrukh S, Wu D, Al-Dadah R, Gao W, Wang Z. A review of integrated cryogenic energy assisted power generation systems and desalination technologies. *Appl Therm Eng*. 2023 Feb;221:119836.

[14] Qin Y, Zhang H, Hou S, Wang F, Zhao J, Zhang C, et al. An efficient high-temperature PEMFC/membrane distillation hybrid system for simultaneous production of electricity and freshwater. *Int J Hydrogen Energy*. 2022 Mar;47(23):11998–2014.

[15] Yang S, Peng S, Xiao Z, Liu Z, Deng C, Du W, et al. Energetic and exergetic analysis of a biomass-fueled CCHP system integrated with proton exchange membrane fuel cell. *Int J Hydrogen Energy*. 2023 Apr;48(36):13603–16.

[16] Qin Y, Zhang H, Zhang X. Integrating high-temperature proton exchange membrane fuel cell with duplex thermoelectric cooler for electricity and cooling cogeneration. *Int J Hydrogen Energy*. 2022 Nov;47(91):38703–20.

[17] Taheri MH, Seker U, Akkurt GG, Mohammadpourfard M. Design, evaluation, and optimization of an integrated proton exchange membrane and double flash geothermal based organic Rankine cycle multi-generation system fed by a biomass-fueled gasifier. *Sustain Cities Soc*. 2024 Feb;101:105126.

[18] Zaheer AHM, Gzara L, Iqbal A, Macedonio F, Albeirutty M, Drioli E. Exergetic analysis of direct contact membrane distillation (DCMD) using PVDF hollow fiber membranes for the desalination brine treatment. *Heliyon*. 2023 Oct;9(10):e20927.