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Status and Trends of Membrane Technology for Wastewater Treatment: A Patent Analysis

Graziela Salvan Cerveira [1,2,*], Jorge Lima de Magalhães [3,4] and Adelaide Maria de Souza Antunes [1,2]

1 Escola de Química, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro 21949-900, Brazil
2 Instituto Nacional de Propriedade Industrial (INPI), Rio de Janeiro 20090-910, Brazil
3 Centre for Technological Innovation/NIT-FAR, Oswaldo Cruz Foundation/FIOCRUZ, Ministry of Health, Rio de Janeiro 21040-900, Brazil
4 Global Health and Tropical Medicine (GHTM), Instituto de Higiene e Medicina Tropical (IHMT), University NOVA of Lisbon (UNL), 1349-008 Lisboa, Portugal
* Correspondence: grazisalvan@yahoo.com.br

Abstract: Global access to clean water and sanitation has been broadly discussed in the context of the Sustainable Development Goals adopted by the United Nations. In this context, membrane technology has been increasingly applied with great success in wastewater treatment. Considering the relevance of patent information for understanding the current status and future trends of technologies, the patent filings on membrane technology for wastewater treatment in the period from 2011 to 2019 were analyzed. This study comprised a global analysis, aimed at determining the most general aspects, and a qualitative analysis, which consisted of a careful reading of the documents to assess technological statuses and trends. From a total of 7303 patent documents found on the topic, 488 documents were selected for the qualitative analysis. China, Japan and the United States play a leading role in the development of these technologies. Companies constitute the vast majority of the applicants. The focus of the inventions turned out to be: equipment, membranes, customized equipment/processes for specific wastewaters, fouling control and cleaning, combinations of technologies and sustainability. Finally, enhancements in the operational performance of the membrane separation equipment and the development of membrane materials with increased water flow and fouling resistance are found to be key factors to broaden the application of membrane separation technology in wastewater treatment.

Keywords: membrane separation; patents; wastewater treatment; technological trends

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1. Introduction

The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity [1]. Global Goal number six is "Clean Water and Sanitation", since communities across the world have been facing water supply challenges due to increasing demand, drought, the depletion and contamination of groundwater, and dependence on single sources of supply [1,2]. The reuse of industrial and municipal wastewater and the recovery of potential pollutants used in industrial processes have become increasingly critical to address these challenges, especially in arid or semi-arid areas, where drinking and irrigation water must be imported at high costs [3]. The future potential for reclaimed treated wastewater is enormous, and can also be justified in view of the growing concern about contamination of water sources with toxic compounds [4]. Advanced treatment technologies have been shown to be able to remove many potentially harmful compounds that were not effectively removed by conventional treatment processes [5].

Various advanced treatment technologies have been developed, tested and applied to meet current requirements and future trends in wastewater treatment. In this context, membrane filtration technology has been increasingly applied with great success [6]. Current, available membranes allow the separation of larger particles such as suspended solids down to smaller ones like ionic elements [7]. Membrane properties, including pore size, wettability, surface charge, permeability, thickness and mechanical strength, may vary according to membrane type and application [8]. The application of membrane technology in wastewater treatment has grown significantly in the last couple of decades due to the many advantages it offers over other wastewater treatment technologies [9]. Some of the benefits include: reduced footprint, the possibility of low or no chemical usage and environmental friendliness [10]. Membrane separation processes can be used alone or in association with other treatment processes, such as post- or pre-treatment, depending on the characteristics of the wastewater to be treated, the flow rate and the desired final quality [11]. Microfiltration, ultrafiltration, nanofiltration and reverse osmosis are the membrane processes most commonly used in wastewater treatment, and can be understood as an extension of the classical filtration processes that use, in this sequence, membranes with increasingly smaller pores [12]. Closer membranes offer a greater resistance to mass transfer, needing to operate at higher pressures [13]. In addition to these, other processes with membranes have gained ground in wastewater treatment, such as membrane bioreactors, electrodialysis, forward osmosis and membrane distillation, and seek to improve selectivity, energy consumption, fouling resistance and capital cost [14].

Patent documents, although not necessarily corresponding to innovations introduced on the market, play an important role in the innovation process, allowing the identification of technological domains that could be covered by new inventions and the relevant technologies, searches for potential partners for the development of new technologies and innovations, and the movements of other scientific, technological and market actors [15–17]. The relevance of technological information from the analysis of patents intensifies as an annual growth in patent documents in the world has been observed; these patents cover all technological fields and can be accessed in national or international offices with electronic media, whose systematization presents objective criteria to perform searches and collect data [18]. In 2020 alone, 3.3 million patents were filed worldwide. The long-term trend in patent applications worldwide is upwards, applications having increased from approximately 1 million in 1995 to around 2 million in 2010 and reaching the 3 million mark in 2016 [19]. Patent documents offer a glimpse of the future, as they describe upcoming technologies that may yet be placed on the market. To illustrate, one could note that the company Toray currently commercializes the TM700D series of brackish water reverse osmosis membranes [20]: composite membranes containing a support material, a porous support layer formed on the base material and a functional separating layer containing polyamide. By conducting a patent search, one finds that this membrane's characteristics and production method closely match the patent application JP2014233652 [21] filed by Toray in 2013.

Many articles analyze the information provided by patent documents to verify the development of new technologies. Mao et al. [22] conducted a patent analysis combined with text mining to quantitatively analyze 11,840 patents related to industrial wastewater treatment in the Derwent Innovations Index database. The study concluded that promising directions of research in the foreseeable future include devices for physical treatments, advanced oxidation processes, and automated and energy-saving treatment systems. Sun et al. [23] analyzed 35,838 patents on the chemical treatment of wastewater. The article observed that the technology's evolutionary path generally showed a transition from biological process-combined chemical treatments to electrochemical treatments and finally to physical process-combined chemical treatments. Even though these works are related to wastewater treatment, they do not focus on membrane technology. Moreover, automated methodologies, such as text mining, lack critical reviews of each document, which will invariably lead to a shallower interpretation of their contents.

In the context of membrane technology for wastewater treatment, numerous scientific articles have been published. Ezugbe and Rathilal [9] present general concepts of the trending membrane technologies in wastewater treatment, including microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, forward osmosis and membrane distillation. According to the authors, fouling and high energy demand remain major issues that need to be overcome. Zhang et al. [24] describe methods for modifying polymer membranes to improve hydrophilicity, anti-fouling and anti-compaction characteristics. As stated in the article, the method of modifying membranes with inorganic nanoparticles has attracted much attention due to its facile operation and manufacturing processes, but it presents some drawbacks that must be overcome to broaden its commercial application, such as the dramatic loss of permeate flux and the non-recyclable nature of the membrane materials. Zheng et al. [25] perform a national survey of membrane plants and membrane manufacturers to investigate the characteristics of membrane technology applications for industrial wastewater treatment to increase water supply in China. The results indicated that 6.7 million m^3 of wastewater per day was treated by applying membrane technology. Due to the increasingly stringent emission standards faced by industries and water resource shortages, it is expected that the membrane technology market will grow in the next decades to cope with the water issues in China. In spite of the great number of studies that address topics related to membrane technology for wastewater treatment, a thorough survey of the patent activity on the subject is missing. It is thus the purpose of this study to fill this gap. Therefore, considering the increasing importance of environmental protection and the relevance of patent information for understanding the current status and future trends of technologies, this work aims to present the main developments regarding the application of membrane technology in wastewater treatment, based on the information available in patent documents. The information was analyzed under two aspects: a global analysis, aimed to determine the most general aspects, and a qualitative analysis, which consisted of a careful reading of documents. This article is useful for different stakeholders (academics, governments, businesses and society) to keep track of the development of technology in the field.

2. Methodology for the Search and Analysis of Patent Documents

2.1. Search of Patent Documents

The Derwent Innovations Index is a commercial database that covers over 39 million patent documents from 40 worldwide patent-issuing authorities in the field of chemistry, electrics, electronics and engineering. Therefore, this database was used to search for patents. After running multiple retrieval experiments and pre-literature research, customized search strategies were developed for each membrane separation process applicable to wastewater treatment: microfiltration, ultrafiltration, nanofiltration, reverse osmosis, membrane bioreactor, electrodialysis, forward osmosis and membrane distillation. The advanced search was conducted on the Derwent Innovation Index website using keywords and the International Patent Classification (IPC) (the specific Boolean retrieval is shown in Appendix A). The IPC is the international classification system created by the Strasbourg Agreement (1971) which divides technological areas in classes from A to H. Within each class, there are subclasses, main groups and groups in a hierarchical system, with classifications for the technological contents of the patents. The patent search included documents indexed in the database in the period from 2011 to 2019. A total of 7303 patent applications were found and were imported into an Excel spreadsheet. As patent applications are often filed in more than one country, constituting a patent family that shares the same priority application, it is important to mention that, in this work, patents with the same priority were counted only once.

2.2. Analysis of the Patent Documents

The information retrieved from the patent documents found in the search was analyzed under two aspects: a global analysis and a qualitative analysis. The global analysis aimed to determine the most general aspects, such as the countries of origin and the profiles of the applicants. The qualitative analysis, on the other hand, consisted of a careful reading of documents. Due to the large number of documents found in the search, only some of them were selected for the qualitative analysis. The choice of documents for the qualitative analysis was made considering countries with the highest number of priority applications, as well as the number of documents per applicant for each of the membrane separation processes applicable to wastewater treatment. In addition, the selection criteria considered if the documents had been protected in more than one country. Although China has a large volume of patent filings, most filings are made exclusively in China. An exception was the membrane distillation process, for which all documents were read, since it was the one with the fewest documents resulting from the search. The set of documents selected for the qualitative analysis was read and classified, identifying the main objectives and characteristics of the inventions and separating them into different categories. Thus, it was possible to identify the statuses and trends of technological developments.

3. Results and Discussion

3.1. Global Analysis

Table 1 shows the number of patent documents found in the search for each of the processes, the total number of documents retrieved and the total after removing repeated documents. A total of 7303 documents related to membrane separation for wastewater treatment resulted after removing the repeated ones.

Table 1. Number of patent documents found in the search divided by the type of membrane separation process, retrieved from the Derwent Innovations Index database, indexed between 2011 and 2019 (own research).

Process	Number of Patent Applications
Microfiltration and Ultrafiltration	735
Nanofiltration	710
Reverse osmosis	2215
Membrane bioreactor	3638
Electrodialysis	443
Forward osmosis	270
Membrane distillation	95
Total	**8106**
Total after removing repeated documents	**7303**

Figure 1 shows the evolution of patent documents published on the subject in the 2011–2019 period. The number of patent applications published each year varied from a minimum of 436 (in 2011) to a maximum of 1295 (in 2018). It is important to mention that the number of documents published in 2018 and 2019 is underestimated because patent applications have a period of secrecy, which is generally about 18 months from the filing date, and their indexation in the database occurs after their publication. The growing number of patent documents published over the last few years suggests that research and development has been carried out systematically and proves the relevance of membrane separation for wastewater treatment.

According to the country or organization of priority, China stands out with 5843 filings (about 80% of the total number of filings), followed by Japan with 458 filings, as presented in Figure 2. In third and fourth place are, respectively, the United States with 376 filings and South Korea with 270 filings. The priority documents from these four countries (China, Japan, the United States and South Korea) represent around 95% of the total. The European Patent Office is in fifth place with 74 filings. On the other hand, according to the WIPO's report of worldwide patent-filing activity in 2020 [19], China's IP office reported a total of 1.5 million patent applications, followed by the United States (USPTO; 597,172), Japan (JPO; 288,472), the Republic of Korea (KIPO; 226,759) and the European Patent Office (EPO; 180,346). Together, these five offices accounted for 85.1% of the worldwide total. Therefore, in the field of membrane technology for wastewater treatment, patent filings seem to be more geographically concentrated in these main countries when compared to the global patent-filing statistics.

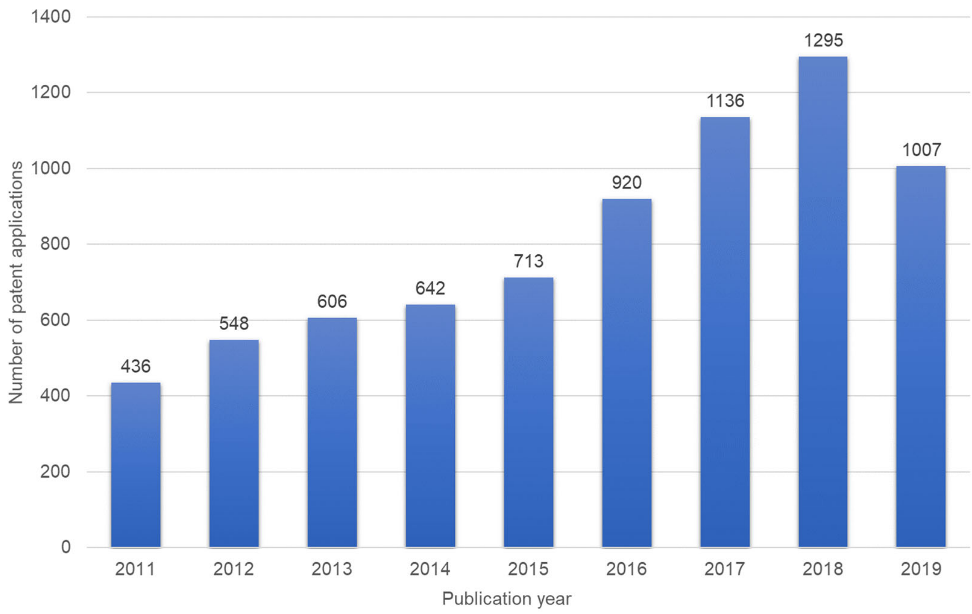

Figure 1. Evolution over time of patent applications published on membrane separation technology for wastewater treatment, retrieved from the Derwent Innovations Index database, indexed between 2011 and 2019 (own research).

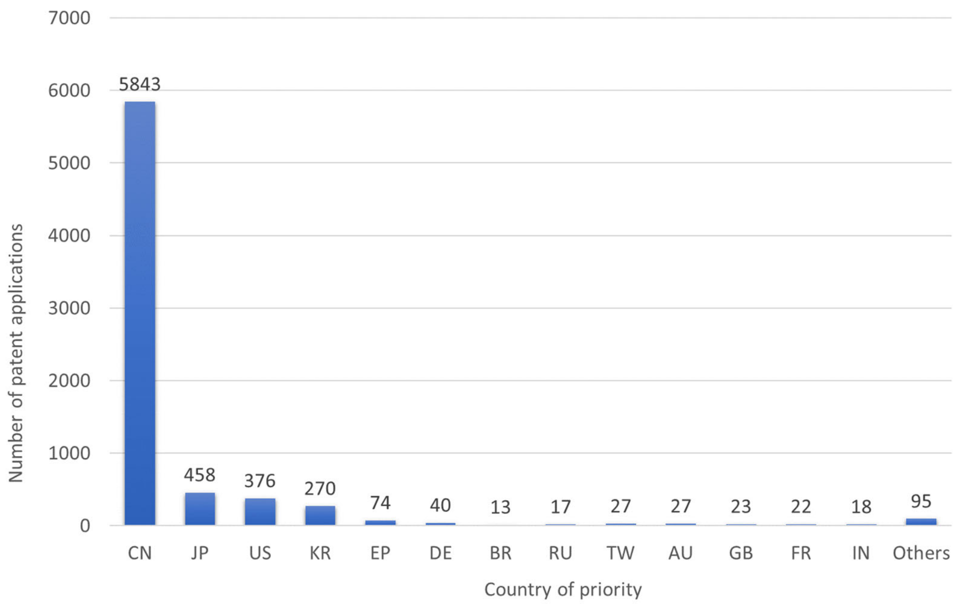

Figure 2. Number of patent applications about membrane separation technology for wastewater treatment per country of origin, retrieved from the Derwent Innovations Index database, indexed between 2011 and 2019 (own research). Country codes: AU (Australia); BR (Brazil); CN (China); DE (Germany); EP (European Patent Office); FR (France); GB (United Kingdom); IN (India); JP (Japan); KR (South Korea); RU (Russian Federation); TW (Chinese Taipei); US (United States).

However, the distribution profile of patent filings by country of origin changes significantly when sole patent applications that have been subject to protection in multiple countries or organizations are considered. In this case, China loses importance, as the vast majority of Chinese patent applications are filed exclusively in China. The evaluation of patent applications filed in multiple countries or organizations is interesting as a potential indicator of the relevance and international coverage of the subject being protected.

It is reasonable to assume that technologies that have commercial interest are protected in multiple countries, to prevent inventions from being copied by competitors. Therefore, it is particularly interesting to analyze these deposits, since they are more attractive in terms of technological development. Figure 3 shows the distribution of patent filings by country of origin, considering patent applications filed in multiple countries. A total of 708 sole applications, which correspond to 9.7% of the patent applications found in the search, were filed in multiple countries. Using this approach, filings originating from the United States predominate (228 documents, 32% of the total), followed by Japan (165 documents, 23% of the total). China ranks third, as 75 Chinese patent applications were filed in multiple national patent offices. Thus, it is worth noting that, out of a total of 5843 patent documents of Chinese origin shown in Figure 2, only 1.3% of them were filed in multiple countries. Figure 3 also indicates that there is a significant number of patent applications originally filed in the European Patent Office and in some European countries, especially in Germany, France and the United Kingdom. In addition, approximately 3% of patent applications originated from Australia.

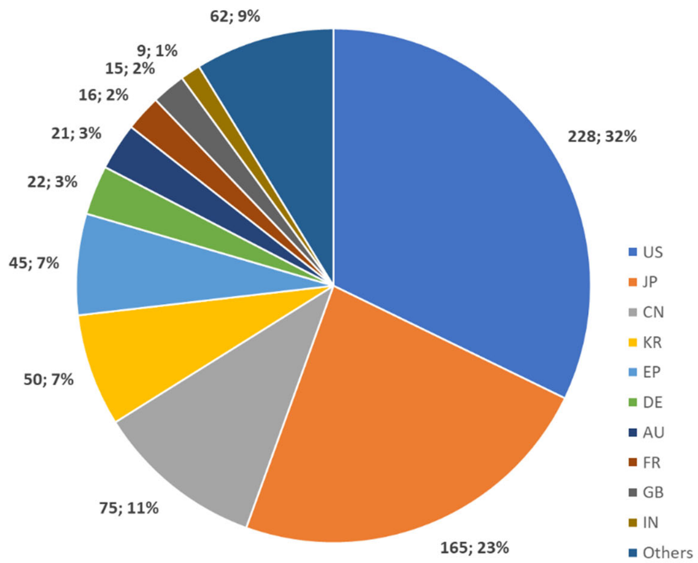

Figure 3. Number of patent applications about membrane separation technology for wastewater treatment per country of origin, considering only the applications filed in multiple countries, retrieved from the Derwent Innovations Index database, indexed between 2011 and 2019 (own research). Country codes: AU (Australia); CN (China); DE (Germany); EP (European Patent Office); FR (France); GB (United Kingdom); IN (India); JP (Japan); KR (South Korea); US (United States).

Companies are the most important type of applicant in the period of search, accounting for 6671 patent applications, which represents 91.3% of the total. A total of 632 sole patent applications were filed by individuals, without mentioning the name of a company. This indicates that there is great commercial interest in membrane separation technology for wastewater treatment.

Large companies stand out as the main technology developers, as can be seen in Figure 4. The graph in Figure 4 exclusively considers the applicants whose patent applications were protected in multiple countries, in order to cover technological developments that have greater relevance and an international scope. The graph includes applicants who have at least 10 patent applications filed in multiple countries. As stated by Pavitt [26], patent statistics at the level of individual firms reflect the total volume of innovative activities in these firms. Therefore, the identification of the main applicants in the sector is helpful to determine which firms are performing research and development and are seeking to protect their inventions.

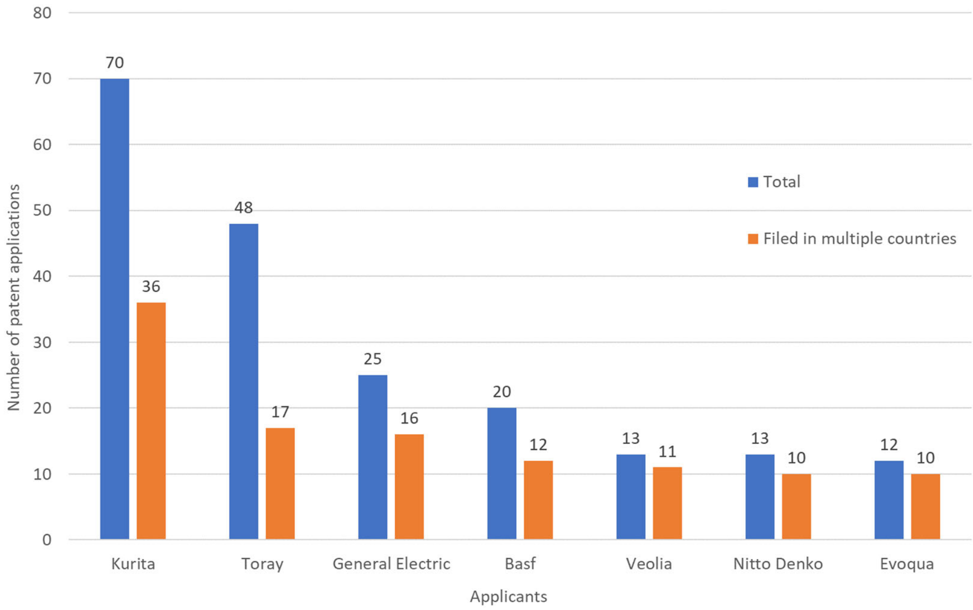

Figure 4. Main applicants about membrane separation technology for wastewater treatment whose applications were filed in multiple countries, retrieved from the Derwent Innovations Index database, indexed between 2011 and 2019 (own research).

Some general information about the seven main applicants is presented as follows.

- Kurita is a multinational Japanese supplier of chemicals and equipment for water treatment;
- Toray is a multinational chemical industry headquartered in Japan, and it has several areas of activity, including the manufacture of reverse osmosis membranes;
- General Electric (GE) is a US-based company that operates in several fields, such as: medical technologies, energy, aeronautics and renewable energy. GE had a subsidiary called GE Water and Process Technologies, which was a world leader in the systems and services field for industries, providing state-of-the-art solutions in water and wastewater; it was acquired by the French company Suez in 2017. According to the analysis of patent applicants, the ownership of existing patents remains with GE and has not been changed to Suez;
- Basf is a global German chemical company and a world leader in the chemical field. The company is organized into six segments: chemistry, materials, industrial solutions, surface technologies, nutrition and agricultural solutions;
- Veolia is a French water, waste and energy management services company. The services provided by the company include the treatment and reuse of industrial wastewater;
- Nitto Denko is a Japanese company dedicated to the production of various products, such as adhesives, for the automotive, industrial, construction, healthcare, metallurgical, electrical and electronic markets. The company's portfolio also includes the supply of polymeric membranes for reverse osmosis, nanofiltration and ultrafiltration, for uses such as water treatment and wastewater reuse;
- Siemens Water Technologies was acquired in 2013, changing its name to Evoqua Water Technologies. The US-based company is a leader in water and wastewater treatment products, systems and services for industrial and municipal customers.

3.2. Technological Trends

As explained in Section 2, the documents read for the qualitative analysis were selected because they were from the main applicants of each of the membrane separation processes applied to wastewater treatment. In total, 488 documents were read to generate the global technological panorama. It was found that, although the search was carried out for each of the membrane processes, a significant part of the documents was related to more than one membrane separation process. For example, if a patent document describes a membrane, the inventors often claim that it could be applied both to nanofiltration and to reverse osmosis, just by varying the size of its pores. Furthermore, some inventions require a combination of multiple membrane separation processes, such as forward osmosis combined with membrane distillation. Therefore, it was considered more appropriate to present the qualitative analysis in terms of the type of solution proposed by the documents, rather than in terms of the membrane separation process to which it refers. During the reading of the documents, the following categories were assigned to the inventions, depending on their main objectives:

- Equipment;
- Membrane;
- Customized equipment or process for specific wastewaters;
- Fouling control and cleaning;
- Combination of technologies;
- Sustainability.

In the following topics, the analyses of documents belonging to each of the categories are presented.

3.2.1. Equipment

The inventions that are focused on equipment are usually directed at improving the operational performance of the membrane separation system. Some of the most frequent objectives of the inventions are linked to increasing the permeate flux in the membrane [27], facilitating the washing and maintenance of equipment [28], preventing leaks in the membrane sealing system [29], preventing fouling [30] and increasing the durability of the equipment [31]. In fact, these points represent bottlenecks in membrane separation processes and need to be overcome in order to expand their application in water and wastewater treatment.

For example, one of the inventions discloses a radial split-ring seal for use in spiral reverse osmosis systems [29]. The seal has an inner circumference/diameter selected to fit in a groove in an outer surface of a seal plate. The outer circumference/diameter is selected to be larger than the diameter of the inner surface of a cylindrical housing that receives the seal plate. A gap is centered along the radius of an annulus of a filtration system. The inner and outer diameters of the annulus and the width of the gap are selected to obtain a tight fit between an outer circumference of the annulus and the inner surface of the housing. These constructive features provide the effective sealing of the spiral membrane element, reducing leakage and providing mechanical stability.

3.2.2. Membrane

A large number of the documents studied are dedicated to membranes made of polymeric materials, which can be attributed to their cheaper costs compared to inorganic materials. This is in accordance with other works which mention that membranes used for wastewater treatment are typically polymeric [8,13]. Novel polymer materials are developed in the patent documents analyzed, such as: an ultrafiltration membrane made from a copolymer which comprises a polyarylene ether block and a hydrophilic-hydrophobic block containing a polyisobutene block [32]; and a microfiltration membrane comprising a functional layer of polyamide and a coating that contains polymer made from a quaternary ammonium repeating unit covering the functional layer [33].

Moreover, a significant number of the inventions are about composite membranes, which proves the interest in such types of membranes in the optimization of permeate flux. The importance of composite membranes is also supported by evidence in the literature [34,35].

From the study of the information provided by the patent documents, it is noted that some of the properties most frequently sought in membrane materials are chemical and mechanical stability, increased water flow, fouling resistance and selectivity. In fact, the improvement of these properties is essential to expand the application of membrane separation processes in wastewater treatment.

The membranes, as described in the patent documents, may be applicable to more than one separation process. As a matter of fact, the most important difference between microfiltration, ultrafiltration, reverse osmosis and forward osmosis is the size of the membrane pores, so that the same membrane material can be applied to more than one process. Membrane distillation and electrodialysis, however, require membranes with different characteristics from the other processes due to their different working principles. In the case of electrodialysis, the membranes used are ion exchange membranes. In membrane distillation, the hydrophobic nature of the material is important so that the liquid does not enter the pores.

3.2.3. Customized Equipment or Process

The documents belonging to this category propose customized equipment or treatment steps for specific wastewaters. Most of the documents are specifically directed to the treatment of industrial wastewater. A few documents mention that the treated wastewater can be domestic or industrial. Regarding the sectors in which the industrial wastewater is generated, it is possible to identify a great variety of industries, with emphasis on oil and gas, refinery, petrochemicals, chemicals, electronics, food and beverage, mining and tobacco industries. It turns out that the choice of treatment steps depends a lot on the characteristics of the wastewater to be treated, as well as the desired final purity level. Many of the documents analyzed provide for a pre-treatment to be carried out before the membrane separation step. Some of the most commonly proposed pretreatments are pH adjustment [36], ion exchange [37], filtration and precipitation [38]. Specific contaminant removal steps can also be indicated, such as nitrogen removal by precipitation [38] and sulfur removal by desulfurization [39].

3.2.4. Fouling Control and Cleaning

The presence of fouling in the membrane is undesirable, as it causes a drop in the permeate flux, which implies a reduction in the yield of the process. Thus, the development of operating and cleaning methods that reduce membrane fouling is of fundamental importance to increase the competitivity of membrane separation technology. Membrane fouling is one of the main issues to be solved in membrane separation processes, as already mentioned by other authors [40–42].

One of the proposed strategies in the inventions for fouling control is the use of chemical agents, such as coagulants and polymers, to inhibit the formation of deposits on the membrane and/or to serve as a cleaning agent. Examples of the new cleaning agents developed in the patents analyzed include: a composition of tannic acid and an organic compound with a molecular weight of 60–500 containing an amino group [43]; and a modified tannin obtained as the Mannich reaction product of an amine, an aldehyde and a tannin [44].

Another strategy is the improvement of the processes' operation methods. With this purpose, the inventions disclose the development of a specific configuration for the membrane backwash system [45], an operation with reduced permeation flux [46], and the installation of an apparatus with oscillating motion to move the foulants from the submerged membrane for the membrane bioreactor process [47].

3.2.5. Combination of Technologies

Combinations of technologies are applied in order to obtain greater efficiency in the removal of organic loads to optimize the footprint required by the treatment plant and to reduce operating costs. Other important motivations for combining technologies are the increasingly strict quality standards for treated wastewater and the growing interest in reusing it.

Many of the inventions associate biological treatments with membrane filtration. For instance, a solution is proposed for the treatment of electronic industrial wastewater by removing suspended solids, followed by reverse osmosis and a biological treatment with activated carbon [48]. This process has the advantage of efficiently removing low-molecular weight organic substances, in addition to reducing the total organic carbon value of the recycled water by using equipment with low footprint requirements. Another example of an invention involving the combination of technologies is a membrane bioreactor configured to treat the effluent from a dissolved air flotation unit [49]. The utilization of the dissolved air flotation system reduces the need of aeration in the membrane bioreactor used to oxidize the wastewater, as well as the amount of chemicals used during the membrane cleaning cycle, resulting in reduced operating costs. In addition, the reduced organic load results in less membrane fouling, allowing the membrane filtration unit to operate with a lower surface area and a higher flow rate.

3.2.6. Sustainability

In view of the importance of seeking a balance between the availability of natural resources and their exploitation, sustainability has become an increasingly relevant aspect in the design of wastewater treatment systems. The reuse potential of treated water, in addition to the use of renewable energies and energy reuse, are important criteria to be considered in the development of new technologies.

Many of the inventions provide for the recycling of treated water. For example, one of them describes a wastewater treatment system comprising a lime-softening reactor, a microfilter and a nanofiltration membrane unit [50]. The concentrate from the nanofiltration membrane unit is recycled to the nanofiltration unit through the lime-softening reactor and the microfilter. The system serves as a reuse plant for industrial wastewater, such as coke wastewater, landfill leachate, textile factory wastewater or brine. Another possibility of water recycling is proposed in a system comprising a rapid filtration unit, ultrafiltration and reverse osmosis, in which the concentrate from the reverse osmosis is used for backwashing the rapid filtration unit [51].

The minimization of energy consumption is also an important issue, especially in membrane distillation processes in which wastewater must be heated. The use of solar energy and heat recycling are important focuses of research and innovation to address this subject [52,53].

Table 2 presents a summary, including the main applicants and some examples of the inventions.

Table 2. Summary of the patent applications about membrane separation for wastewater treatment selected for the qualitative analysis, retrieved from the Derwent Innovations Index database, indexed between 2011 and 2019 (own research).

Category	Applicants *	Examples of Technical Solutions
Equipment (120 documents)	Midea Group, Toray, General Electric, Nitto Denko, Korea Inst Sci & Tech, Dow, Asahi Kasei	• Filtration element for use in ultrafiltration with a permeate collecting tube that is arranged in the outer portion of the filtration element [27]; • Radial split-ring seal for use in a spiral reverse osmosis system. It has an annulus having diameters and a gap with width, in which the diameters and width are selected to obtain the fit between the outer circumference of the annulus and the inner surface of the housing [29]; • Flow–path element for a forward osmosis membrane element. A second network with both surfaces flatter than those of the first network is positioned at double the surface side of the first network [31]; • Fluidized bed anaerobic wastewater treatment system with a rotary disc that is equipped within a membrane bioreactor for inducing the turbulence of foul water with rotations of a rotary disc [54]; • Useful system for treating feed water comprising a bipolar electrodialysis device to receive the salt-concentrated solution, and an ion exchange regeneration system to flow the regenerating solution through the ion exchange device [55].
Membrane (102 documents)	Toray, Basf, Nitto Denko, Samsung, Sabic, National University of Singapore and Basf, Fujifilm, Membrane Distillation Desalination, General Electric	• Composite semipermeable membrane used for recovering ultrapure water from wastewater treatment, comprising a base material, porous support layer and separation-functional layer made of polyamide [56]; • Copolymer used for an ultrafiltration membrane, comprising a polyarylene ether block and hydrophilic–hydrophobic block containing a polyisobutene block [32]; • Separation membrane used in the manufacture of ultrapure water, comprising a separation-functional layer made of polyamide, and a coating made of a polymer of a quaternary ammonium repeating unit, covering a functional layer [33]; • Curable composition useful for preparing a membrane, comprising a cross-linker made of at least two acrylamide groups, a curable ionic compound, solvent, and free radical initiator [57]; • Composite hydrophilic–hydrophobic membrane used in a membrane distillation system, comprising a hydrophilic polymer layer, a hydrophobic polymer layer and fluorinated surface-modifying macromolecules [58].
Customized equip./process (97 documents)	Kurita, Boying Xiamen Sci & Tech, Sinopec, Sumitomo, General Electric, Veolia	• Processing of cationic surfactant-containing wastewater discharged from an electronic industrial process. This involves adjusting the pH of the wastewater, and performing a reverse osmosis treatment of the wastewater [36]; • Removing selenium by directing the wastewater stream to an ion-exchange unit containing a resin or an adsorption media unit followed by a nanofiltration unit [37]; • Processing landfill leachate by removing ammonia nitrogen, flocculating, electrolyzing, carrying out capacitance desalination, anaerobic and aerobic treatment, filtering using a membrane, and processing the concentrated solution [38]; • Processing apparatus of a radioactive effluent from a waste liquid which contains radioactive substances. It comprises a pre-processor, a membrane separator (hollow fiber membrane or flat film), a reverse osmosis membrane apparatus, and piping [59].
Fouling control and cleaning (64 documents)	Kurita, Toray, General Electric, Basf	• Membrane filtration method used for the treatment of water. It involves backwashing the filtration membrane of pre-treatment membrane module using pre-treated water diverted by a branch pipeline [45]; • Operating method for a reverse osmosis membrane apparatus used for the biological treatment of water. It involves an operating apparatus consisting of an osmotic membrane element with a membrane unit and a preset permeation flux [46]; • Cleaning agent for cleaning liquid for a reverse osmosis membrane, comprising an aliphatic amide and/or an aromatic amide [60]; • Agent for improving the blocking rate of a reverse osmosis membrane for the processing of water containing organic compounds, including an amino group-containing compound with a preset molecular weight and tannic acid [43].

Table 2. *Cont.*

Category	Applicants *	Examples of Technical Solutions
Combination of technologies (59 documents)	Kurita, General Electric, Mitsubishi, JFE, Korea Inst Sci & Tech, Evoqua	• Treating electronic industrial wastewater by performing a suspended solid removal process, reverse osmosis membrane separation treatment process, and biological activated carbon treatment process [48]; • Treating organic wastewater by separating organic wastewater into permeated water and concentrated water using a reverse osmosis membrane, and performing the biological treatment of the concentrated water [61]; • Processing industrial wastewaters loaded with organic pollutants by electrochemically removing organic components from wastewater and then reducing the chemical-oxygen demand value, and concentrating the organic pollutants in liquid using nanofiltration and reverse osmosis [62].
Sustainability (46 documents)	Kurita, Toray, Boying Xiamen Sci & Tech, General Electric, Hydration Systems	• Wastewater treatment system, useful in industrial wastewater reuse plants. It includes a lime softening reactor, microfilter, and nanofiltration membrane unit, in which feed water flows to a nanofiltration unit through a reactor and a microfilter [50]; • Reuse of a cooling effluent, which involves processing the effluent water by circulating a cooling water system with a dispersing agent, and a water collecting system containing a turbidity-removal installation [63]; • Operating electrodialysis device that directs the feed streams to thedilution and concentration compartments, recycles the reject stream, discharges the reject stream, and replaces it with the feed stream [64].

* Applicants with more than two patent applications.

4. Conclusions

This article presented a patent analysis of membrane separation for wastewater treatment, in order to help understand the current status of and identify future trends for this technology. Some important findings include:

- An increasing number of patent documents have been published over the last decade, indicating that research has been carried out systematically and showing the relevance of membrane technology in the field of wastewater treatment;
- Most of the patent applications have originated from China, which accounts for about 80% of the total filings in the period of 2011 to 2019. However, when only the patent applications filed in multiple countries are considered, the high-priority countries are the United States (32%) and Japan (23%);
- Companies, such as Kurita, Toray, General Electric, Basf, Veolia, Nitto Denko and Evoqua, constitute the vast majority of applicants for patents on membrane separation applied to wastewater treatment. This demonstrates that there is significant commercial interest in the development of related technologies.

Careful reading of the selected patent documents led to the following classification of the focuses of the inventions: equipment, membrane, customized equipment/processes for specific wastewaters, fouling control and cleaning, combinations of technologies and sustainability. After cross-referencing the individual analyses of these categories, the following conclusions can be highlighted:

- Improving the operational performance of the membrane separation system is found to be a key factor in the application of membrane technology for wastewater treatment;
- The development of membrane materials with an increased water flow and fouling resistance is an essential research line to expand the use of membrane technology;
- Solutions targeting water recycling, renewable energies and heat recovery are already important today, and are likely to expand in the near future. This is due to the increasingly stringent emission standards, as well as global water and energy resource shortages.

Future works may include studies on competitive intelligence: prospective technology that can match current commercial products to previously granted patents, thus evaluating which firms have produced or licensed their technologies.

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Appendix A

Table 1. Search strategy used in the Derwent Innovation Index database.

Process	Search Strategy
Microfiltration and Ultrafiltration	TS = ((ultrafilt* OR ultra-filt* OR microfilt* OR micro-filt*) and (wastewater or waste-water or sewage or effluent)) AND IP = (B01D-061/14 OR B01D-061/16 OR B01D-061/18 OR B01D-061/20 OR B01D-061/22 OR B01D-063* OR B01D-069* OR B01D-071*)
Nanofiltration	TS = ((nanofilt* OR nano-filt*) and (wastewater or waste-water or sewage or effluent)) AND IP = (B01D-061/00 OR B01D-061/02 or C02F-001/44 OR C02F-009/02 OR B01D-063* OR B01D-069* OR B01D-071*)
Reverse osmosis	TS = ((reverse and osmosis) and (wastewater or waste-water or sewage or effluent)) and IP = (B01D-061/02 OR B01D-061/04 OR B01D-061/06 OR B01D-061/08 OR B01D-061/10 OR B01D-061/12 OR C02F-001/44 OR B01D-063* OR B01D-069* OR B01D-071*)
Membrane bioreactor	TS = ((membrane and (bioreactor* OR bio-reactor*) OR MBR) and (wastewater or waste-water or sewage or effluent)) AND IP = (C02F-009/14 OR C02F-003/00 OR C02F-003/02 OR C02F-003/12 OR C02F-003/28 OR C02F-003/30 OR B01D-063* OR B01D-069* OR B01D-071*)
Electrodialysis	TS = (electrodialysis AND (wastewater or waste-water or sewage or effluent)) and IP = (B01D-061/42 OR B01D-061/44 OR B01D-061/46 OR B01D-061/48 OR B01D-061/50 OR B01D-061/52 OR B01D-061/54 OR C02F-001/469 OR C02F-009/06 OR B01D-063* OR B01D-069* OR B01D-071*)
Forward osmosis	TS = ((forward and osmosis) and (wastewater or waste-water or sewage or effluent)) and IP = (C02F-001/44 OR B01D-063* OR B01D-069* OR B01D-071*)
Membrane distillation	TS = ((membrane and distillation) and (wastewater or waste-water or sewage or effluent)) and IP = (B01D-061/36 OR B01D-063* OR B01D-069* OR B01D-071*)

TS: command for searches in the title and abstract; IP: command for searches in the International Patent Classification.

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