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A bibliometric analysis of published literature on membrane photobioreactors for wastewater treatment from 2000 to 2022

Elisabet Segredo-Morales *, Enrique González, Andrés Figueira and Oliver Díaz

Departamento de Ingeniería Química y Tecnología Farmacéutica, Universidad de La Laguna. Avda. Astrofísico Francisco Sánchez s/n. Facultad de Ciencias, Sección Química, 38206, San Cristóbal de La Laguna, Santa Cruz de Tenerife, Islas Canarias, España

*Corresponding author. E-mail: esegredm@ull.edu.es

ES-M, 0000-0002-5671-8965; EG, 0000-0002-8851-5046; OD, 0000-0001-8259-8381

ABSTRACT

With the focus on limiting greenhouse gas emissions, microalgae-based technology is a promising approach for wastewater treatment, combining cost-effective operation, nutrient recovery, and assimilation of CO_2. In addition, membrane technology supports process intensification and wastewater reclamation. Based on a bibliometric analysis, this paper evaluated the literature on membrane photobioreactors to highlight promising areas for future research. Specifically, efforts should be made on advancing knowledge of interactions between algae and bacteria, analysing different strategies for membrane fouling control and determining the conditions for the most cost-effective operation. The Scopus® database was used to select documents from 2000 to 2022. A set of 126 documents were found. China is the country with the highest number of publications, whereas the most productive researchers belong to the Universitat Politècnica de València (Spain). The analysis of 50 selected articles provides a summary of the main parameters investigated, that focus in increasing the biomass productivity and nutrient removal. In addition, microalgal-bacterial membrane photobioreactor seems to have the greatest commercialisation potential. S-curve fitting confirms that this technology is still in its growth stage.

Key words: bibliometric analysis, membrane, microalgae, photobioreactor, wastewater

HIGHLIGHTS

- Research trends in MPBR technology were analysed from 126 indexed publications.
- The growth of MPBR technology is mainly driven by the higher biomass productivity and nutrient removal capability when using different types of wastewater.
- A limited number of studies have assessed long-term fouling performance.
- Research analysis revealed the research gaps involved in assessing the parameters that govern the economics.

1. INTRODUCTION

In recent decades, the industrial sector has sought more sustainable processes with lower energy consumption, and the wastewater treatment sector is no exception. In addition, industrial and urban wastewater with high nutrient concentrations represent serious environmental risks such as eutrophication if not properly treated (Liu & Hong 2021). Traditional wastewater treatment systems such as activated sludge, or advanced treatments such as membrane bioreactors, which use micro and/or ultrafiltration membranes, require high amounts of energy for nutrient removal (Asano *et al.* 2007). Therefore, in recent years, less energy-intensive processes have been developed. Among them, the technology of membrane photobioreactors (MPBR) stands out, whose suspension is fully or partially illuminated, allowing the growth of microalgae in the suspension (Fallahi *et al.* 2021). Microalgae are a group of simple uni- or multicellular photosynthetic microorganisms of eukaryotic and prokaryotic cells (Wang *et al.* 2014) that possess qualities such as the ability to reproduce rapidly, adapt adequately to the environment and, above all, have the ability to convert nutrients present in a medium into biomass using solar energy due to their high photosynthetic efficiency (Liu & Hong 2021). It has been widely demonstrated that microalgae use the nutrients present in all types of wastewater to grow efficiently (Li *et al.* 2019).

A membrane photobioreactor (MPBR) is a system that operates continuously and that combines a photobioreactor with an integrated or separate system that uses a micro or ultrafiltration membrane for the separation of the produced biomass (Luo *et al.* 2017). In recent years, new MPBR have been designed using forward osmosis and ion exchange membranes (Zhao *et al.* 2023).

These MPBR arise as a solution to the low sedimentation capacity of biomass and its resulting loss, as well as the limitations of conventional photobioreactors (Luo *et al.* 2017). They are designed to maximise access to natural or artificial light and provide the necessary conditions for algae growth (Alcántara *et al.* 2015). Some authors consider this type of photobioreactors as hybrid photobioreactors (Vo *et al.* 2019; Sirohi *et al.* 2022), since they combine a photobioreactor with a flat panel system or an airlift type column inside which a microfiltration or ultrafiltration membrane can be inserted (Kumar *et al.* 2020). As reported in the literature, the application of membrane photobioreactor technology to water treatment is carried out in closed or semi-closed reactors where the membrane allows the complete retention of the biomass, obtaining a high-quality permeate. As in the case of conventional membrane bioreactors, the main advantage of the technology is the ability to decouple the hydraulic residence time from the solids residence time, which allows process optimisation (Luo *et al.* 2017). In addition, minimising the fouling of the membrane during the filtration process is key to achieving proper operation, as insufficient control can lead to a substantial increase in operating costs and energy consumption (Azizi *et al.* 2021b).

The use of MPBR for wastewater treatment is a recent technology with many avenues for study, both in terms of optimal operating parameters for the performance of the process and in terms of species suitable for obtaining products of a certain value.

The analysis of operational parameters of an emerging technology as well as possible future trends is complex since it is difficult to reach a macro perspective point of view. Bibliometric studies are a powerful tool to analyse scientific advances qualitatively and quantitatively in a particular area (Wallin 2005). According to Pritchard (1969), bibliometric studies are mathematical analyses through statistical analysis of the scientific production and who generates this literature. Bibliometric studies make it possible to evaluate the interest of the scientific community in a specific field by means of statistical and mathematical methods on the number of scientific contributions (articles, books, conference papers, or patents), references, and use of keywords (Mao *et al.* 2021). Bibliometric studies can be divided into two categories: the first focuses on scientific production and the second on the interaction relations of the different authors, understood as the interrelationships between different countries, institutions, and keyword usage. In the first category, the analysis of the global, institutional, or individual scientific production facilitates the increase of knowledge and information on a field of study, favouring the analysis of future trends. On the other hand, the second category allows for the identification of the degree of interest in each region, as well as the interrelationships between the different research groups. The analysis of keywords and their concurrence is crucial to establish the scientific community's perspective quickly and effectively on a particular field (Ramos-Rodríguez & Ruíz-Navarro 2004; de Battisti & Salini 2013). Many authors are including bibliometric analyses to analyse the current status of many water treatment technologies, e.g., industrial wastewater treatment (Mao *et al.* 2021), sulphate removal from wastewater (Ding & Zeng 2022), municipal wastewater treatment (Marcal *et al.* 2021), desalination treatments (Zapata-Sierra *et al.* 2022), and zero brine discharge (Díaz *et al.* 2022). However, there is no such document on an emerging technology such as MPBR for wastewater treatment. The bibliometric study allows the identification of technological trends and advances in membrane bioreactors. In addition, it allows to analyse and compare different operating parameters to determine the optimum operating conditions for a developing technology. A comprehensive view of the technology is provided by bibliometric studies such as the one presented in this manuscript, which allows us to analyse the blueprint in the field of membrane photobioreactor.

The aim of this paper is to highlight the interest that the membrane photobioreactor has aroused in authors in recent years by carrying out a bibliometric analysis which presents a detailed analysis of the current state of the art of the technology, focusing on the operating parameters studied for the optimisation of the process and presenting possible trends for future research.

2. METHODS

The bibliometric review has been conducted using the Scopus database (www.scopus.com), which has more than 25,000 titles from over 5,000 international publishers and a total of 77.8 million publications (Elsevier 2020). It covers diverse fields such as medicine, arts, humanities, technology, and science and has digitised records since 1970.

The search was carried out at the end of April 2023 and publications have been found dating back to the year 2000. The choice of search terms is key for the data to be truly representative of the study being carried out. In this case, it was decided to take as representative those publications in which the terms '*Photobioreactor*', '*Membrane*' and '*Wastewater*' appear in the title, abstract or keywords. Table 1 shows the search equation used.

The impacts of the publications analysed were performed using the Scimago Journal and Country Rank (SJR) and CiteScore from Scopus. Microsoft Excel was used to analyse the data obtained after the search. The world scientific production was represented by using the mapping tool provided by Microsoft Excel, which uses a coloured scale to identify the most productive countries. In this case, the grey colour suggests zero production and the increase in the intensity of the blue colour indicates a higher production. Vosviewer software (version 1.6.17) was used to obtain the figures relating to co-occurrence of the keywords. The software selected is a tool that allows the construction and visualisation of bibliometric networks in the field under study. In this study, a representation by nodes is used. The size of the node is proportional to the use of the keyword and the thickness of the lines of connection between nodes specifies the strength of concurrence of the keywords. In addition, the colour scale allows us to analyse the temporal evolution of the use of the keywords, since the programme indicates the temporality of the highest number of co-occurrences.

A total of 135 publications were found, of which 1 was discarded because, after analysis, it was not related to the subject, 8 because their year of publication was 2023 for not being representative (at the time of the search the year had not ended). Therefore, 126 publications were analysed relating to the application of MPBR to wastewater treatment.

Finally, S-curve analysis makes it possible to estimate and predict the evolution of a technology in order to assess its maturity. The development of many things follows the S-growth curve, including the four stages of emerging, growth, maturity, and aging (Braun *et al.* 2000). Recently, many authors have used this type of curve to evaluate the state of maturity of a process or technology (Mao *et al.* 2021; Marcal *et al.* 2021; Ding & Zeng 2022). Typically, the S-growth curve can be expressed by the following equation.

$$N = \frac{K}{1 + e^{-a(t-b)}} \quad (1)$$

where N represents the cumulative publications annually, t represents the time variable, a and b are kinetic model parameters and parameter K is the 'publication ceiling value' in this study which represents the estimated maximum number of publications that the scientific community is expected to produce on the topic under analysis (Mao *et al.* 2021). The fitting of the experimental data to the S-growth curve was carried out using Origin Pro software.

3. RESULTS AND DISCUSSION

3.1. Documents and temporary distribution

Of the 126 publications found, the majority are scientific articles, nearly 87%, followed by communications to congresses, which account for 6% of the publications, with book chapters and conference reviews being a very small minority. Zapata-Sierra *et al.* (2022) indicate that the analysis of the type of publication can give an idea of the level of maturity of a topic among authors. Thus, a high degree of books and reviews among the publications can indicate a high degree of maturity, while a high percentage of conference presentations indicates a new and emerging technology. The results, therefore, justify that MPBR are growth and maturity phase (Zapata-Sierra *et al.* 2022), due to the high number of scientific articles. Another aspect to analyse the interest of the scientific community in MPBR is to analyse the percentage of results in this field compared to the number of papers published on photobioreactors. A search in SCOPUS using only the keywords 'photobioreactor' and 'wastewater' with the same temporal limitation (2000–2022) shows a total of 848 documents. Therefore, about 15% of the publications on photobioreactors relate to the use of MPBR. The percentage may seem low, but it must be

Table 1 | Search equation and results

Database	Search equation	Results	Temporal limit
Scopus	TITLE-ABS-KEY (membrane AND photobioreactor AND wastewater) AND (EXCLUDE (PUBYEAR, 2023))	135	2000–2022

considered that photobioreactors are a process without a consensus among the scientific community and therefore present a high heterogeneity of design and technological proposals (Sirohi *et al.* 2022). On the other hand, achieving the separation of algae from treated water necessitates a well-coordinated integration of a biological reactor and a separation system. In addition to MPBR, numerous alternative separation processes exist, including microalgae biofilm; microalgae-fungus co-culture, microalgae-activated sludge co-culture, and microalgae auto-flocculation (Huang *et al.* 2023). The main advantage of membrane photobioreactor processes is the total separation of the suspension from the treated wastewater, which represents a great benefit and an improvement in treatment efficiency.

Table 2 shows the time evolution of the documents displayed by the database and the ratio of authors per document. The data show a growing interest of the scientific community in the subject of MPBR. Between the years 2018 and 2021, the number of publications reached a peak. However, in the year 2022, a peak was observed reaching 26 publications, a number higher than the number found in the whole of the years 2021 and 2020. It is worth noting that there was no appreciable interest in the subject until 2011, when at least four publications per year can be found. The ratio of number of authors per paper allows an estimation of the interest of the scientific community, as it gives an idea of the number of researchers interested in the topic under analysis. However, no clear trend can be seen in the number of authors per document, remaining, over all the years at values of between 4 and 6 authors per document, with an average value of 5.15 ± 1.5, with a maximum value of 9.25 in 2014 and a minimum value of 2.67 in 2015.

Many authors have used an S-curve growth model to try to predict the behaviour of scientific output on a particular topic (Mao *et al.* 2021; Marcal *et al.* 2021; Ding & Zeng 2022). Figure 1 shows the fit of real data to the modelling. The results reveal that membrane photobioreactor technology most likely is currently in the development and maturity phase. In this section, the main future trends of this technology are presented.

Additionally, most of the documents have been published in English and only one document has been published in another language, namely French (Malériat *et al.* 2000).

3.2. Areas of publication

The point of view from which the authors have analysed this topic can be determined by analysing the areas of publication automatically provided by the Scopus database. In this case, 12 publication areas have been detected, 7 of which have more than 10 publications. The distribution of publications by area and the temporal distribution in the five main areas are shown in Figure 2.

Table 2 | Documents and ratio author/documents per year

Year	Num. documents	Cumulative documents	Num. author	Author/documents
2022	26	126	143	5,50
2021	14	100	83	5,93
2020	14	86	70	5,00
2019	15	72	63	4,20
2018	16	57	70	4,38
2017	9	41	44	4,89
2016	10	32	41	4,10
2015	3	22	8	2,67
2014	4	19	37	9,25
2013	5	15	21	4,20
2012	3	10	13	4,33
2011	4	7	27	6,75
2010	1	3	6	6,00
2009	1	2	5	5,00
2000	1	1	5	5,00

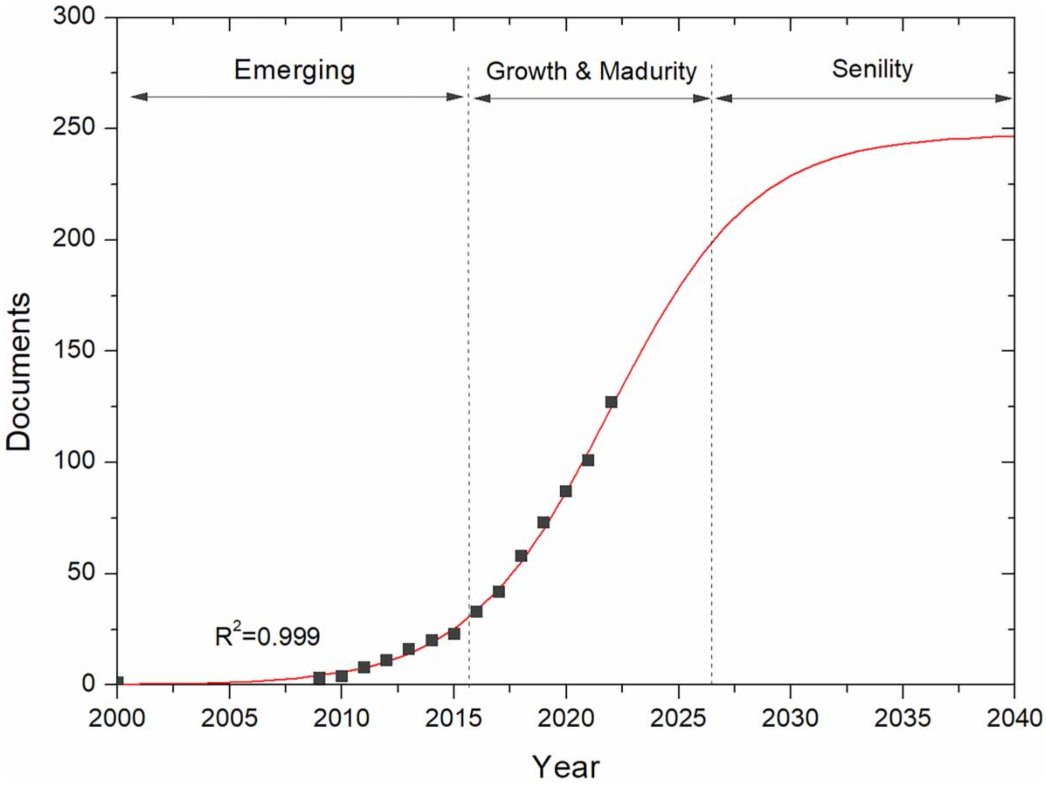

Figure 1 | Future trends for scientists' interest growth regarding membrane photobioreactors (*N* represents the cumulative number of documents published).

Environmental Sciences stand out from the rest of the areas, with a steady upward trend over the years studied, accounting for 33% of the publications found. Next are the areas of Chemical Engineering and Energy, with 18 and 15%, respectively, followed by Engineering, with 10%, and Chemistry and Biochemistry, Genetics and Molecular Biology with

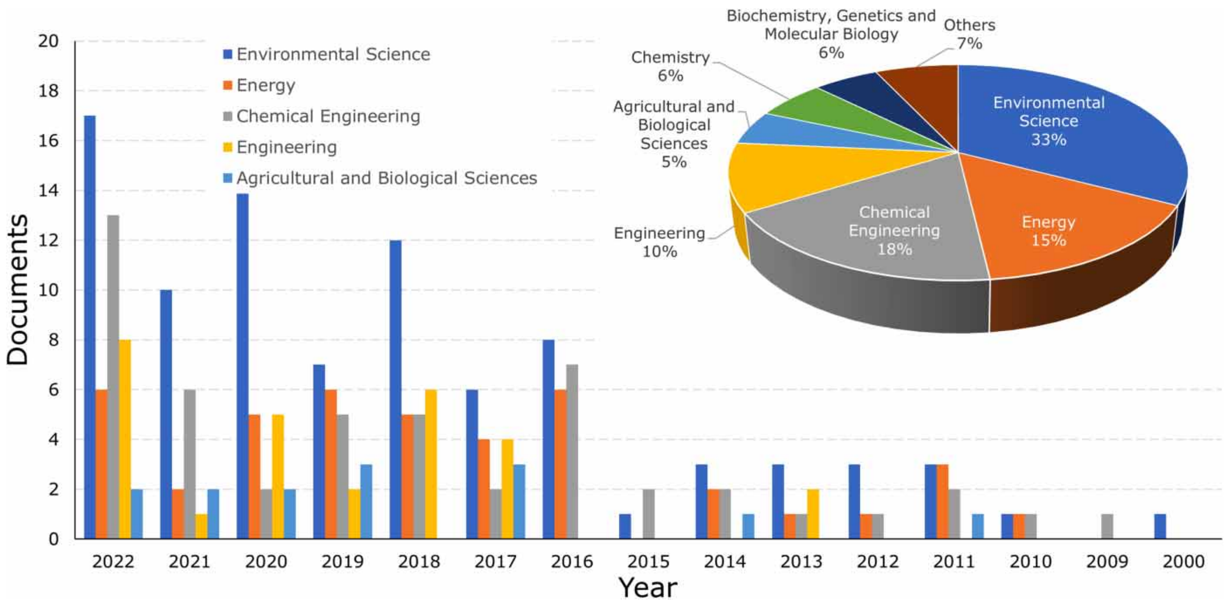

Figure 2 | Evolution of documents published per year in the five main areas of publication.

6% each, and Agricultural and Biological Sciences, with 5%. Publications in the remaining areas accounted for only 7% of the total number.

Within each of the areas, the most cited articles are shown in Table 3. It should be noted that for the areas of Energy and Chemical Engineering, the most cited article is the same and three of them focus on nutrient removal by means of a membrane photobioreactor (Ruiz-Martinez *et al.* 2012; Gao *et al.* 2016a; Praveen *et al.* 2018).

3.3. Publication sources

One of the most decisive aspects when carrying out a bibliometric analysis is the determination of the main publication sources of the authors. Their identification helps to analyse those sources, journals, books, publishers, etc., in which to carry out the search prior to initiating research or, alternatively, possible avenues of publication of future studies. In this case, we have analysed those sources with more than four publications on the subject, obtaining the results shown in Table 4. All sources analysed with more than four documents are journals.

The journal Bioresource Technology, published by Elsevier, is the preferred journal by authors for their publications on this topic, with 23 publications, well above the next highest one. Among the top journals shown in Table 4, only Membranes and

Table 3 | Most cited publications in the main areas of knowledge

Area	Title	Author	Year	Source	Cites	Reference
Environmental Science, Environmental Engineering, Ecology	Continuous microalgae cultivation in aquaculture wastewater by a membrane photobioreactor for biomass production and nutrients removal	Gao F.; Li, Chen; Yang Z.-H.; Zeng, Guang-Ming; Feng, Li-Juan; Liu, Jun-zhi; Liu, Mei; Cai, Hui-wen.	2016	Ecological Engineering	210	Gao *et al.* (2016a)
Energy & Fuels, Agricultural Engineering, Biotechnology & Applied Microbiology	Microalgae cultivation in wastewater: nutrient removal from anaerobic membrane bioreactor effluent	Ruiz-Martinez, A., Martin Garcia, N., Romero, I., Seco, A., Ferrer, J.	2012	Bioresource Technology	153	Ruiz-Martinez *et al.* (2012)
Chemical **Engineering**, Environmental Engineering	Enhancing microalgae cultivation in anaerobic digestate through nitrification	Praveen, P.; Guo, Y.; Kang, H.; Lefebvre, C.; Loh, K.-C.	2018	Chemical Engineering Journal	81	Praveen *et al.* (2018)
Biotechnology & Applied Microbiology, Multidisciplinary Chemistry, Chemical Engineering, Environmental Engineering, **Chemistry**	A hollow fiber membrane photobioreactor for CO_2 sequestration from combustion gas coupled with wastewater treatment: a process engineering approach	Kumar, A.; Yuan, X. Sahu, A.K.; Ergas, S. J.; Van Langenhov, H.; Dewulf, J.	2010	Journal of Chemical Technology and Biotechnology	97	Kumar *et al.* (2010)

Table 4 | Sources with more than four publications on membrane photobioreactors

Source	Documents	Editorial	ISSN	CiteScore (2022)	SJR (2022)
Bioresource Technology	23	Elsevier	0960–8524	17.4	11.889
Water Research	8	Elsevier	0043–1354	18	13.400
Chemosphere	7	Elsevier	0045–6535	11.7	8.943
Science of the Total Environment	7	Elsevier	0048–9697	14.1	10.754
Membranes	7	MDPI	2077–0375	3.7	0.61

Water Science and Technology are in quartiles below Q1 as shown in Figure 3 based on the data reported by the Journal Citation Report for the year 2021. The rest are in the first quartile (Q1) for all areas. The annual distribution of publications in these journals is shown in Figure 4.

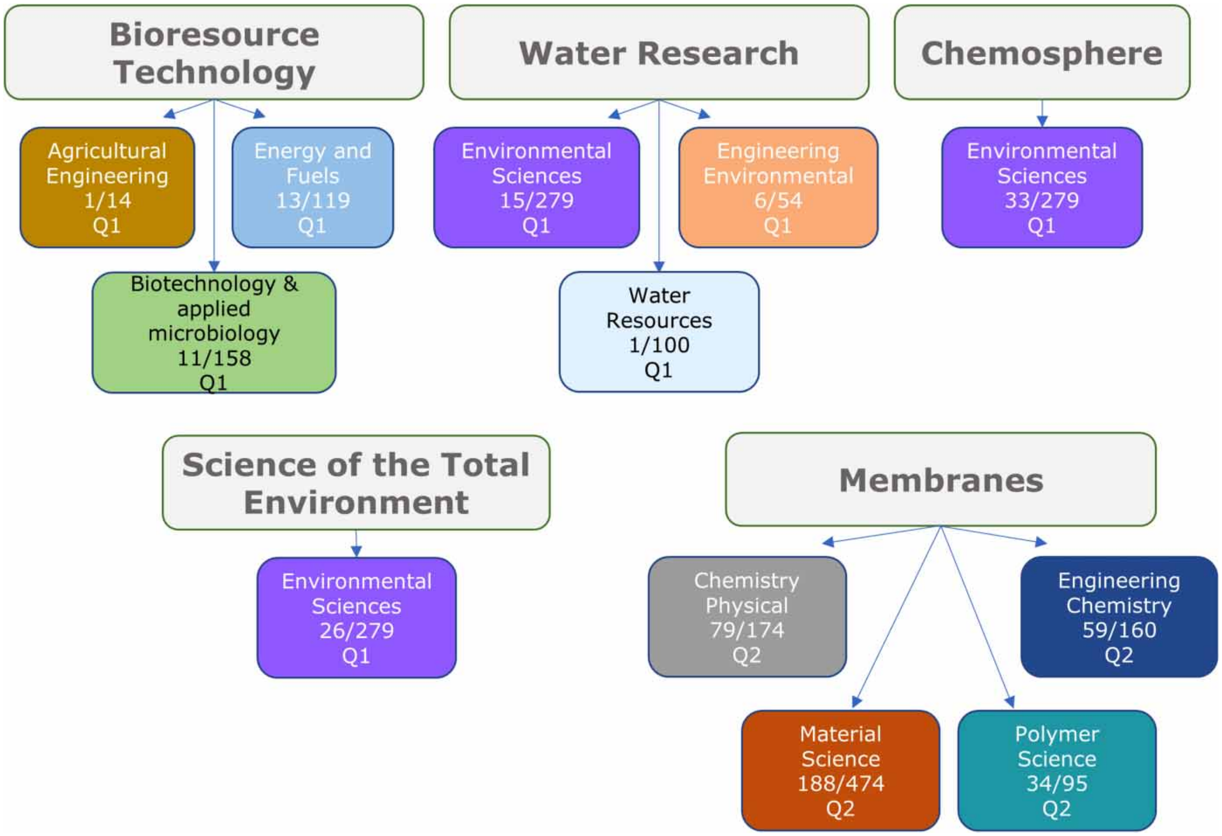

Figure 3 | Journal impact factor ranking of the journals that have published the most on membrane photobioreactors in wastewater treatment. Author prepared based on data from the Journal of Citation Reports for the year 2021.

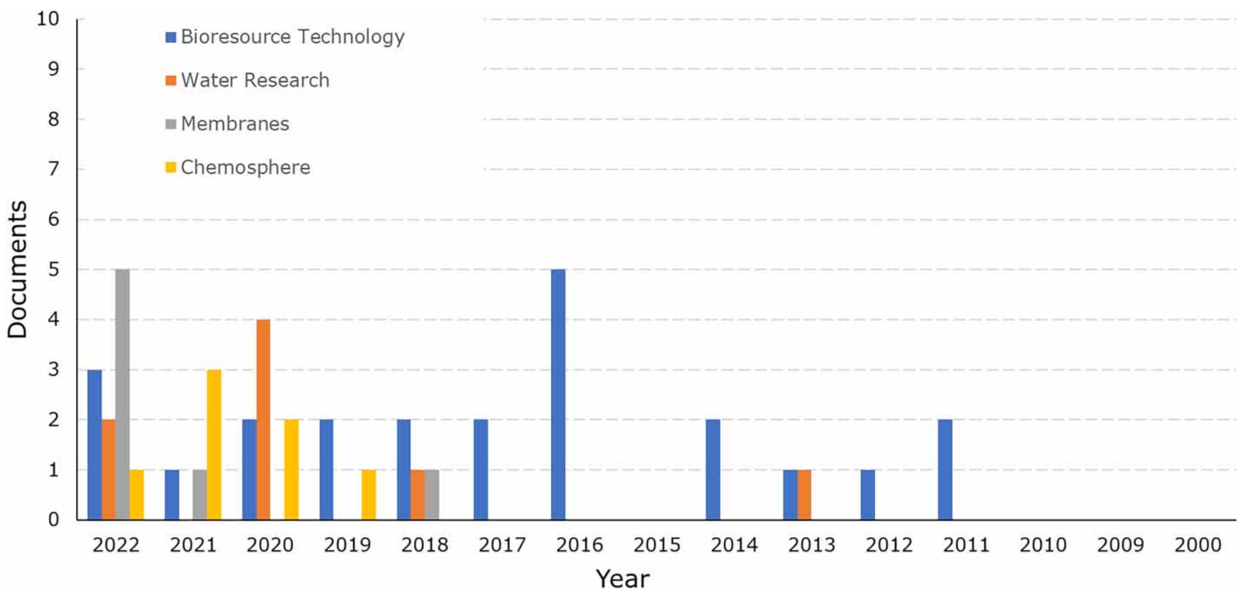

Figure 4 | Evolution of articles in the top five journals by year.

In 2011, the first two publications appeared in the five journals with the most publications, the first journal being Bioresource Technology. From this year on, this journal has been a constant source of publications on the subject, and there has been only a single year in which no articles have been published on the subject. The remaining journals, on the other hand, have shown irregular behaviour, with years without publications on the subject.

Analysing the number of papers published by the journals on MPBR for wastewater treatment, most journals (42 journals) have only published one article on the topic, while a few have published more than one contribution, 16 to be precise. This behaviour was described by the Lotka Law (Price 1976). Figure 5 shows the Lotka Law fit of the results obtained for this search. A high regression of the data was obtained ($R^2 = 0.994$), which shows that the number of journals with many publications on a given topic is low.

3.4. Most cited publications

The five most cited publications on MPBR applied to wastewater treatment are summarised in Table 5. All of them have more than 100 citations each, and only 2 coincide with the most cited publications by area of knowledge shown in Table 3.

Among the most cited articles, two of them are experimental research articles. Specifically, the most cited article deals with the treatment of water from aquaculture by means of a membrane photobioreactor using a pure culture of *Chlorella vulgaris* and *Scenedesmus obliquus* (Gao *et al.* 2016a). *C. vulgaris* showed better performance and was continuously cultivated in MPBR. The significant impact of this study lies in its pioneering demonstration of the remarkable nutrient removal capacity (86.1% for TN and 82.7% for TP) when applied to low-strength wastewater. Notably, the ammonium concentration in the effluent was effectively lowered to levels below 0.002 mg/L. Additionally, the research highlighted the feasibility of achieving substantial biomass productivity (42.6 mg/L day) at low hydraulic residence time (1 day). This capability to operate at low hydraulic retention times (HRTs) has served as a foundation for numerous subsequent studies that have adopted these values (Praveen *et al.* 2016; Novoa *et al.* 2020; Peng *et al.* 2020; Solmaz & Işık 2020). In the third most cited article, the authors evaluate the efficiency of a laboratory-scale membrane photobioreactor for the treatment of an effluent from a submerged anaerobic membrane bioreactor (SAnMBR). They found that this effluent is suitable for the growth of microalgae and where the removal of more than 67% of the ammonium present and about 98% of the phosphorus as phosphate is achieved

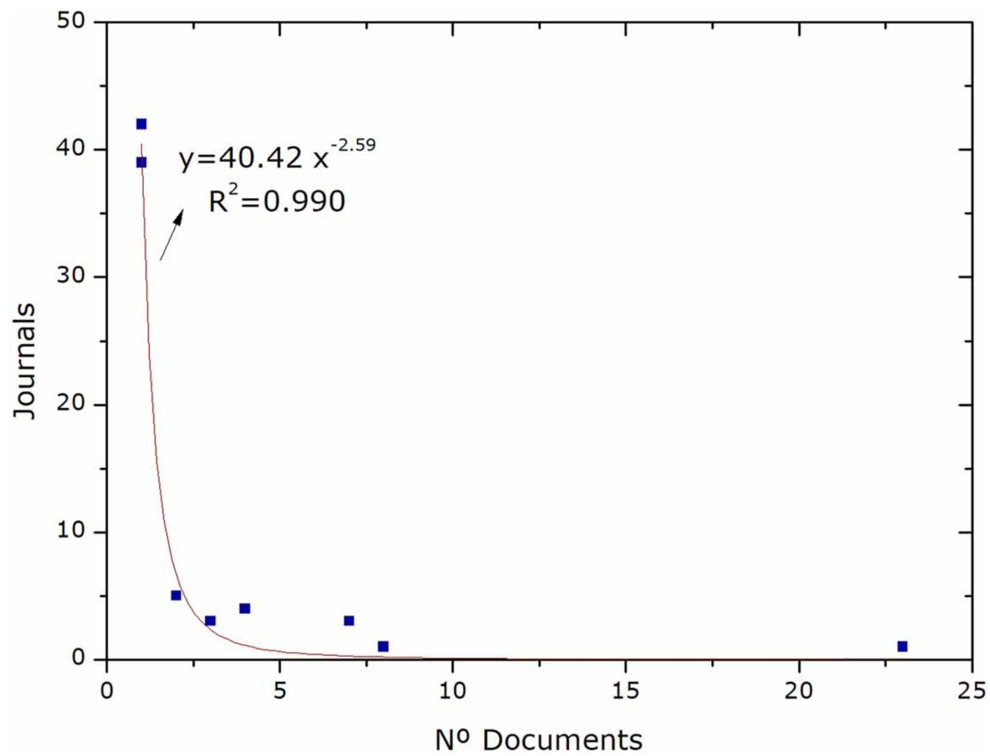

Figure 5 | Lotka Law.

Table 5 | Most cited publications

Title	Authors	Journal	Year	Cites	Reference
Continuous microalgae cultivation in aquaculture wastewater by a membrane photobioreactor for biomass production and nutrients removal	Gao F.; Li, Chen; Yang Z.-H.; Zeng, Guang-Ming; Feng, Li-Juan; Liu, Jun-zhi; Liu, Mei; Cai, Hui-wen.	Ecological Engineering	2016	210	Gao *et al.* (2016a)
Wastewater treatment using microalgae: how realistic a contribution might it be to significant urban wastewater treatment?	Acién, F.G.; Gómez-Serrano, C.; Morales-Amaral, M.M.; Fernández-Sevilla, J.M.; Molina-Grima, E.	Applied Microbiology and Biotechnology	2016	189	Acién *et al.* (2016)
Microalgae cultivation in wastewater: nutrient removal from anaerobic membrane bioreactor effluent	Ruiz-Martinez, A.; Martin Garcia, N.; Romero, I.; Seco, A.; Ferrer, J.	Bioresource Technology	2012	153	Ruiz-Martinez *et al.* (2012)
Simultaneous microalgae cultivation and wastewater treatment in submerged membrane photobioreactors: a review	Luo, Y.; Le-Clech, P.; Henderson, R.K.	Algal Research	2017	124	Luo *et al.* (2017)
A review of membrane fouling and its control in algal-related membrane processes	Liao, Y.; Bokhary, A.; Maleki, E.; Liao, B.	Bioresource Technology	2018	123	Liao *et al.* (2018)

by applying a solid retention time (SRT) of 2 days and operating semi-continuously for 42 days (Ruiz-Martinez *et al.* 2012). The principal contribution of this investigation resided in presenting a tangible proof of concept, wherein a mixed polyculture of indigenous species exhibited robust growth and proved to be efficacious in nutrient removal from real wastewater. Subsequent studies have emphasised this crucial finding (Marbelia *et al.* 2014; Xu *et al.* 2014; Praveen *et al.* 2019; Peng *et al.* 2020).

The other most cited publications are reviews, ranking in the top five in second, fourth, and fifth positions. The second most cited article focuses on the analysis of the conditions affecting the operability of a membrane photobioreactor, the characteristics of the wastewater, biological aspects such as the establishment of algae-bacteria consortia, etc., and how these aspects affect the nutrient removal capacity of the system. In addition, the economic aspects of the process are also studied in comparison with conventional wastewater treatment processes. This study also includes an introduction to the main methods for biomass harvesting and critically describes future trends in this field of study (Acién *et al.* 2016). The fourth most cited article analyses extensively the operational variables that affect the growth of biomass in MPBR, nutrient removal performance, etc. Among the multiple variables, they analyse the effect of pH, hydraulic retention time (HRT), SRT, light, aeration and temperature, as well as considering the interrelationships between these parameters (Luo *et al.* 2017).

3.5. Institutions, countries, and their interrelationships

An analysis of the countries that have been the most productive on the topic is shown in Figure 6. The distribution of publications among the countries makes it possible to determine whether efforts have been made globally on the topic or whether, on the contrary, interest is localised in some areas of the planet. China is the country with the most publications (30), followed by Spain and the USA (with 20 and 12, respectively).

Singapore and Canada finish the list of the five most productive countries with 11 publications each. The interrelationships between countries in publications can give an idea of the degree of collaboration that exists. Table 6 shows, by country, the top five countries with which they have collaborated, in order of highest to lowest interrelationships. The number of documents on which they have collaborated is indicated in brackets.

Table 6 shows that Spain, despite being the second largest producer of publications on the subject, has only collaborated with Italy. By contrast, countries with lower production have a fairly high level of collaboration, for example, Australia and India.

An analysis of the producing institutions has also been conducted to find out whether there are several institutions in a country or whether there is only one institution in charge of research in this field. Figure 7 shows the top 20 most producing institutions. The Universitat Politècnica de València and Universitat de València stands out with 12 documents each, which represents almost 60% of the publications in Spain.

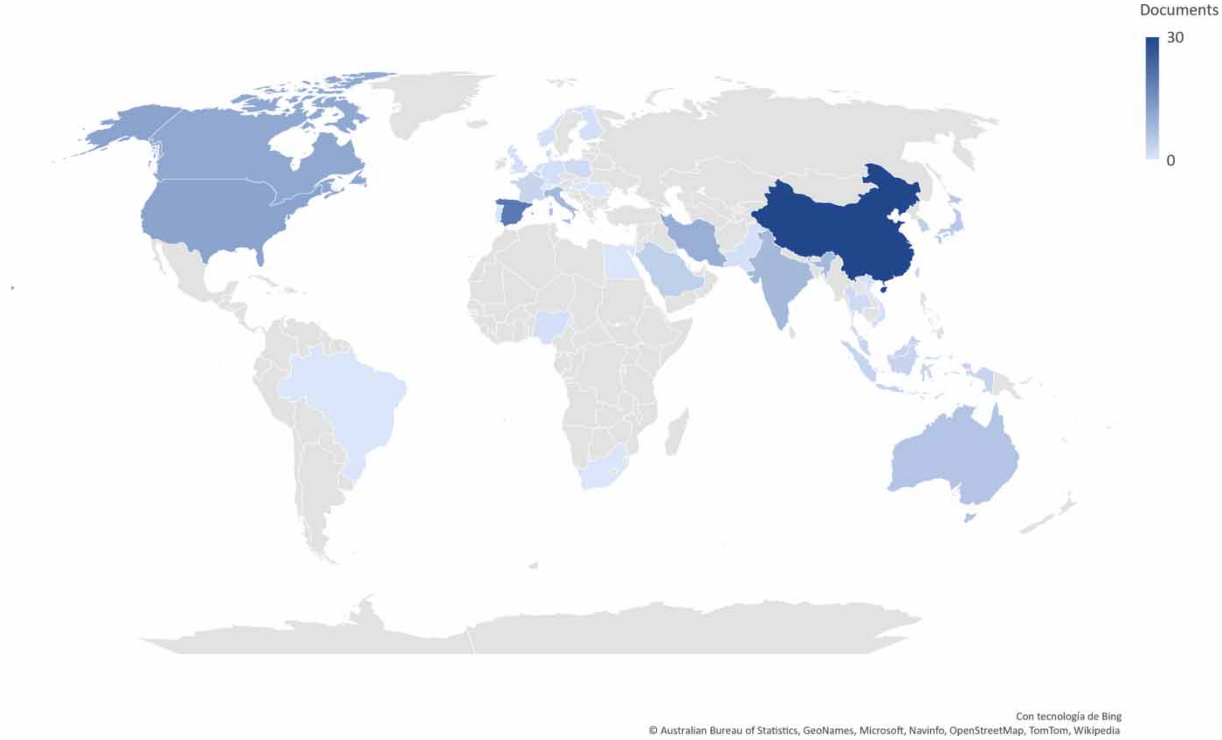

Figure 6 | Geographical distribution of scientific production in membrane photobioreactors.

In third place is the National University of Singapore, which accounted for 100% of Singapore's publications. The 30 publications from China are divided between the Ministry of Education of China, Zhejiang Ocean University, Zhejiang Normal University, and Chongqing University, mostly. However, the country with the most institutions in the top 20 most productive institutions after China is Iran with four, namely Shahid Sadoughi University of Medical Science, Shiraz University of Medical Sciences, Tehran Univesity of Medical Sciences, Islamic Azad University, with three publications each. However, an analysis of these publications shows that they are the same ones for all the centres, i.e., all three publications are collaborations between these five research centres. This corroborates what is shown in Table 6, which shows that Iran has little collaboration with other countries.

Table 6 | Top 10 producing countries and interrelationships

		Partners[a]				
Country	**Documents**	**1**	**2**	**3**	**4**	**5**
China	30	Canada (6)	Singapore (3)	USA (3)	Australia (1)	Benin (1)
Spain	20	Italy (1)				
USA	12	China (3)	Belgium (1)	Canada (1)	Finland (1)	France (1)
Singapore	11	New Zealand (5)	China (3)			
Canada	11	China (6)	Australia (2)	USA (1)		
Iran	10	France (1)	Italy (1)			
India	8	Denmark (1)	Malaysia (1)	United Kingdom (1)		
Italy	8	Denmark (1)	Iran (1)	Poland (1)	Saudi Arabia (1)	Spain (1)
Australia	6	Canada (2)	China (1)	Indonesia (1)		
Japan	5	Thailand (2)	China (1)			

[a]The countries have been ordered according to the number of collaborations carried out, with 1 indicating the country with which the most collaborations and 5 indicating the country where the least have been carried out. The number of documents on which they have collaborated is indicated in brackets.

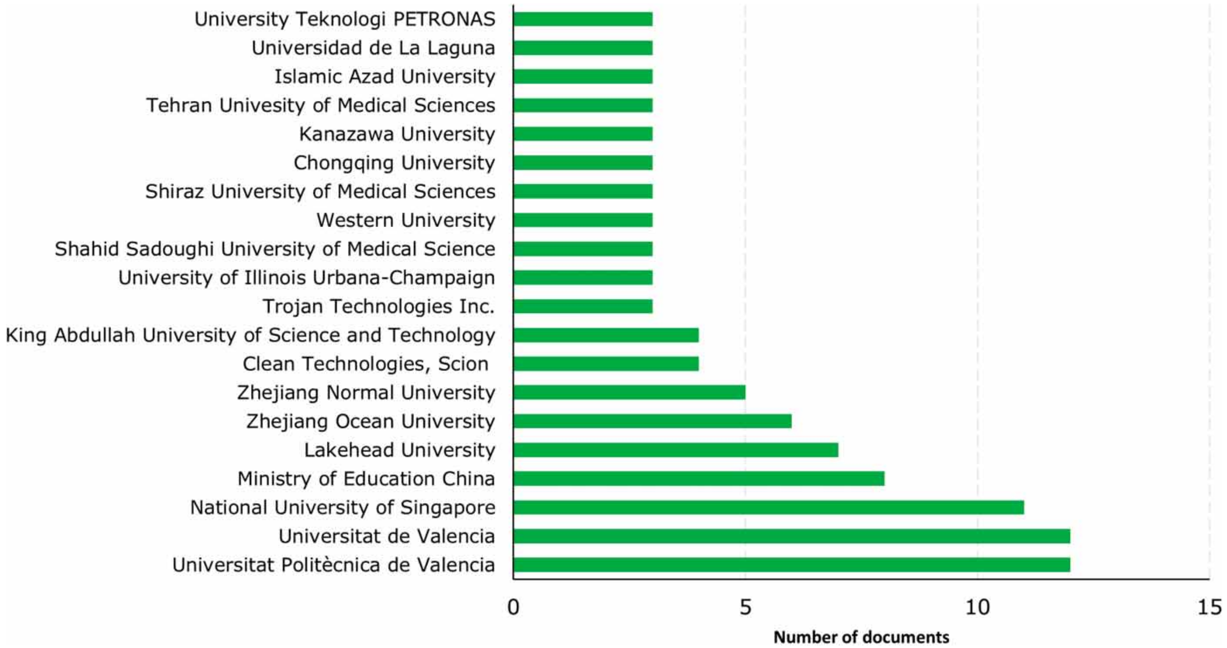

Figure 7 | Top 20 institutions.

3.6. Keywords

Keywords make it possible to analyse the conceptual blocks through which scientific production on a given topic is approached (Delgado Vázquez *et al.* 2019). Figure 8 shows the interrelationships between the keywords used by the authors in the 111 documents found. To estimate this figure, those with a co-occurrence of five times in the last 10 years have been

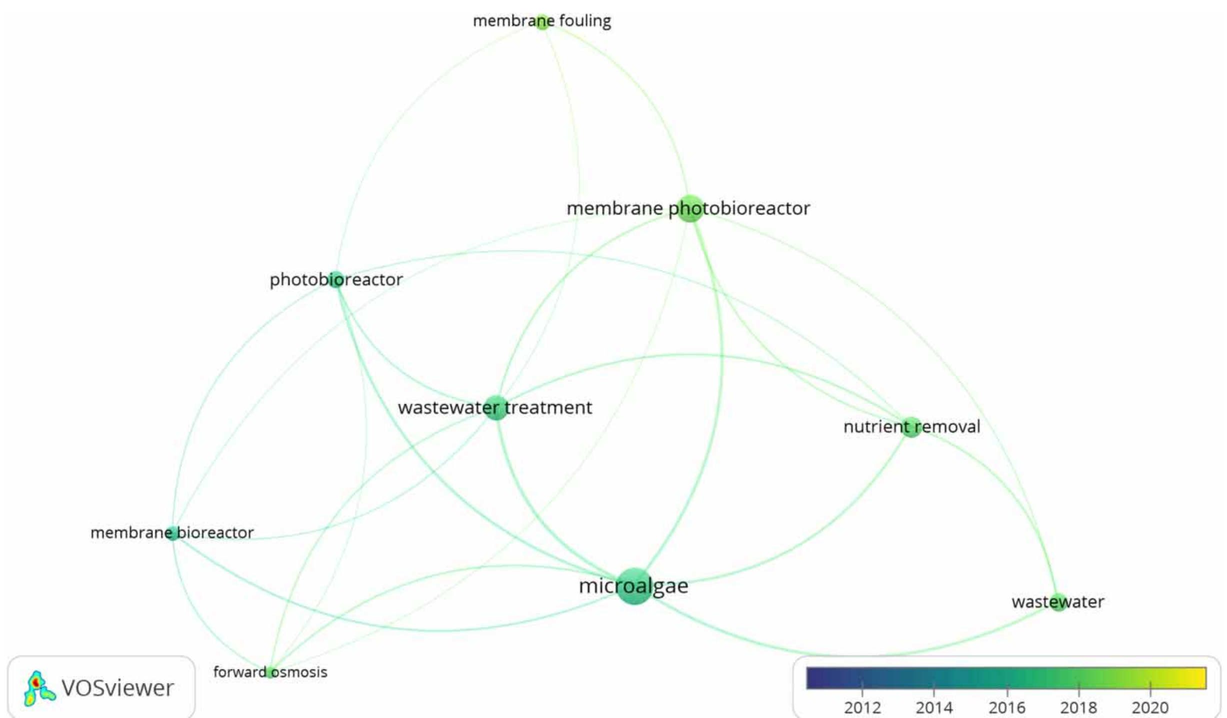

Figure 8 | Temporal evolution of the keywords used by authors over the last 10 years.

taken into consideration and repeated keywords such as 'nutrient removal' and 'nutrients removal' have been eliminated as they are considered the same keyword.

As can be seen, the co-occurrence of keywords used by authors indicates that the use of MPBR focuses on nutrient removal in wastewater treatment. Forward osmosis is also beginning to appear as a keyword because recent studies have used this technology to concentrate secondary treatment effluents as a step prior to the implementation of a membrane photobioreactor, effectively removing N-NH_4^+ and P-PO_4^{3-} (Wang *et al.* 2020) or as a next step after the operation of a photobioreactor that allows for improved nutrient removal with minimal energy consumption (Praveen & Loh 2019). Membrane fouling also appears as a keyword that has been used by the authors in recent years, demonstrating the interest of the scientific community by appearing in 12 articles in the last 10 years. Authors' efforts in this regard have focused on analysing the causes of membrane fouling, identifying the best operating conditions that reduce the deposition of materials on the membrane surface. For example, Lee *et al.* (2018) attribute the causes of fouling to the presence of soluble microbial products (SMP) and/or extracellular polymeric substances (EPS) and attempt to mitigate the presence of these substances by varying the HRT. Others have analysed the effect on fouling of other key parameters, such as exposure to light (Keramati *et al.* 2021) or nutrient loading of the influent (Zhang *et al.* 2021). The control of membrane fouling is a fundamental aspect as it affects the operability of the process because high fouling leads to a reduction in productivity, and an increase in the frequency of membrane cleaning and energy consumption (Liao *et al.* 2018).

3.7. Analysed operating parameters and operating performances of MPBR

This section analyses 50 articles, considered to be the most representative of the research trends developed in the last 10 years (Tables 7 and 8). Three primary research directions have been discerned in the field of investigation: (1) microalgae species and wastewater characteristics, (2) enhancement of operational parameters for optimisation, and (3) examination of process configuration.

3.7.1. Microalgae species and wastewater characteristics

In 70% of the studies, the microalgae *C. vulgaris* (e.g., Singh & Thomas 2012; Marbelia *et al.* 2014; Gao *et al.* 2016a, 2016b; Praveen *et al.* 2018) is used as a reference species, with some other studies using species such as *Scenedesmus obliquus* (Gao *et al.* 2019; Praveen *et al.* 2019), or *Botryococcus braunii* (Lee *et al.* 2018; Lee Jang *et al.* 2020). The feed is mainly municipal wastewater with a low C/N ratio, such as secondary treatment effluent (60%), synthetic (39%) or real (21%). Additionally, other types of industrial wastewater, usually subjected to secondary treatment (electronic device factory (Zhen-Feng *et al.* 2011), livestock industry, (Lee *et al.* 2018; Lee Jang *et al.* 2020), or whey wastewater (Keramati *et al.* 2021)), have been studied.

3.7.2. Operating parameters

In relation to the operating parameters of the process, it is to be noted that microfiltration membranes (0.1–0.5 μm) of PVDF or PES, in hollow fibre or flat plate modules, are mostly used. Low filtration fluxes (1.3–12 L/h m^2) are generally applied, a parameter that is not usually optimised. Studies usually apply continuous artificial (LED or fluorescent lamps) light or 12 h dark/12 h light photoperiods with PAR values between 60 and 300 μmol/m^2 s. Typically, microalgae growth increases with light intensity up to a saturation point. However, beyond this critical saturation threshold, the influence of light intensity on microalgae growth becomes negligible and does not further contribute to the observed growth rate (Wang *et al.* 2018). In addition, it is widely recognised that the provision of exogenous CO_2 through gasification (pure or air-enriched) is often necessary to improve the overall treatment performance (Table 7). Moreover, the introduction of CO_2 through gasification also aids in stabilising the pH at optimal levels, typically ranging between 7 and 8 (Table 7). The regulation of carbonation is generally accomplished by controlling the gasification rate or implementing on-demand injection to manage the pH effectively. Additionally, it should be noted that effective membrane fouling control necessitates air scouring, which can be integrated with the carbonation process. Operating temperature is usually 20–25 °C.

Given the essential role of HRT and SRT values on process performance, a significant number of the studies have focused on optimisation of both parameters (Table 8). Generally, HRT determines the degree of nutrient removal. The values studied are usually between 0.5 and 5 days, the optimisation of which depends on the species and feed characteristics (Marbelia *et al.* 2014; Novoa *et al.* 2020). It is suggested that at values above 1 day, nitrogen and phosphorus removal rates of more than 65 and 70%, respectively, can be achieved (Boonchai & Seo 2015; Gao *et al.* 2016b; Honda *et al.* 2017; Praveen *et al.* 2019). On the other hand, the SRT, which influences microalgae concentration, is usually studied in the range 2–40 days. Since biomass

Table 7 | Main operating parameters analysed in membrane photobioreactors

ID	Process[a]	Feedwater[b]	C[c] (mg/L)	TN (mg/L)	TP (mg/L)	Microbial species	Scale[d]	Membrane[e]	Area (m^2)	Flux (L/m^2 h)	Light	Aeration	Temp (°C)	pH
Gao *et al.* (2016a)	MPBR	RIW	BOD5 (8.5)	6.8	0.4	*Chlorella vulgaris*	L	PVDF, HF, 0.1 μm	0.05	NA	9,000 lux	0.5 L/min, 99.9% CO_2	25	6.8–7.2
Tan *et al.* (2014)	A-MPBR	RISEW	COD (702–1,026)	240.3–382.7	22.7–40.2	*Chlorella vulgaris*	P	DM	0.34	520–57	Outdoor	15–20 L/min, 5–9% CO_2	summer (35–39); winter (7–12); spring (17–22); autumn (23–27)	> 9.25
Marbelia *et al.* (2014)	MPBR	SSEW	–	7.5–22.1	1.7–2.2	*Chlorella vulgaris*	L	PE, FS	4 × 0.016	2.6–13	72 W	5 L/day	15–22	8–9
Chitapornpan et al. (2013)	PAnMBR	RIW	COD (700–9,750)	1.0–35.0	NA	Native purple phototrophic bacteria	L	PE, HF, 0.4 μm	0.04	NA	120 W, IR-2,880 transmitting filter (270 W/m^2)	–	28–39	6–8
Praveen *et al.* (2018)	MPBR	SSEW	COD (124–190)	N-NH_4^+ (25–100); N-NO_3^- (5–51)	10–25	*Chlorella vulgaris*	L	PVDF, HF, 0.1 μm	0.0308	1.33	8,000 lux	1 L/min, 3% CO_2	24–26	NA
Singh & Thomas (2012)	MPBR	RSEW	COD (30–50)	NO_3^- (50–80); NO_2^- (18–25)	PO_4^{3-} (10–20)	*Chlorella vulgaris*	L	PES, 0.45 μm	0.1	12	12 h/12 h (4,000 lux)	4 L/min	24	7.2–7.5
Gao *et al.* (2016b)	MPBR	RSEW	COD (39.9)	13.3	0.8	*Chlorella vulgaris*	L	PVDF, HF, 0.1 μm	0.05	NA	120 μmol/m^2 s	0.5 L/min, 4% CO_2	25–30	6.5–7.8
Praveen & Loh (2016)	O-MPBR	SSEW, STEW	–	8.8–22.8	2.4–6.0	*Chlorella vulgaris*	L	FO (TFC)	0.036	1.28–1.59	1,000–1,500 lux	0.4 vvm, 5% CO_2	NA	NA
Zhen-Feng *et al.* (2011)	MPBR	SISEW	–	8.0–22.0	0.2–1.2	*Scenedesmus* sp. LX1	P	HF, 0.2 μm	10	NA	6,000 lux	10 L/min	NA	7.7–8.5
Praveen *et al.* (2016)	O-MPBR, MPBR	SSEW	–	4.35	1.8	*Chlorella vulgaris*	L	FO (TFC), MF (PVDF)	FO (0.036), MF (0.036)	FO (3.18–6.37); MF (3.18–6.37)	1,500–2,000 lux	0.4 vvm, 5% CO_2	NA	7.0–7.5
Sheng *et al.* (2017)	SB-MPBR	RSEW	–	24.7	3.5	Native microalgae (*Euglena* sp.)	L	PVDF, FS, 0.16 μm	0.012	NA	10,000 lux	1.8 L/min	NA	NA
Peng *et al.* (2020)	B-MPBR	RSEW	COD (7.8)	9.1	4.6	*Chlorella vulgaris*	L	PVDF, HF, 0.1 μm	0.05	0.4	102–112 μmol/m^2 s	0.5 L/min, CO_2	26	NA
Shi *et al.* (2018)	MPBR	SSALW	TOC (58.6)	NA	NA	*Chlorella* sp.	L	Ceramic, FS, 0.1 μm	0.045	3.3	2,000 Lux	0.5 L/min	25	NA
Boonchai & Seo (2015)	MPBR	RSEW	COD (10.5)	18.8	1.0	*Chlorella* sp. ADE4; *Chlorella* vulgaris	L	HDPE, HF, 0.4 μm	0.04	3.75	14 h/10 h (50 μmol/m^2 s)	4 L/min	25	7.5–8.5
Luo *et al.* (2018)	MB-MPBR	SSEW	DOC (9.0)	14.1	2.5	Microalgal-bacterial consortia (dominated by *Chlorella vulgaris*)	L	PVDF, HF, 0.04 μm	NA	4	85 μmol/m^2 s	2 L/min	NA	NA

González-Camejo *et al.* (2020b)	MB-MPBR	RSEW	COD (63)	48.8	4.4	Native microalgae-bacteria consortia (dominated by *Chlorella* sp.)	P	PVDF, HF, 0.03 μm	3.4	NA	Outdoor + artificial LED lamps (277–284 μmol/m^2 s)	Air, CO_2 (pH control)	Outdoor (16.9–18.8)	7.5
Viruela *et al.* (2018)	MB-MPBR	RSEW	COD (31)	51.3	6.8	Native microalgae-bacteria consortia (dominated by *Scenedesmus* sp.)	P	PVDF, HF, 0.03 μm	2 × 31	NA	Outdoor (169–378 μE/m^2 s)	2 m^3/h, 99.9% CO_2 (pH control)	Outdoor (23.9–28.7)	7.5
Gao *et al.* (2019)	MPBR	RSEW	COD (25.6)	12.8	0.6	*Chlorella vulgaris; Scenedesmus obliquus*	L	PVDF, HF, 0.1 μm	NA	NA	102–112 μmol/m^2 s	0.5 L/min, 99.9% CO_2 (pH control)	25–28	6.8–7.5
Chitapornpan *et al.* (2012)	PAnMBR	RIW	COD (700–9,750)	NA	NA	Native purple phototrophic bacteria	L	PE, HF, 0.4 μm	0.04	3.75–7.5	180 W, IR-2880 transmitting filter	–	28–35	7
Lu *et al.* (2021)	MPBR	SSEW	–	40	5	*Chlorella vulgaris*	L	HF, 0.01 μm	NA	NA	140 μmol/m^2 s	0.5–1.0 L/min, 4% of CO_2	28	6.5–7.0
Derakhshan *et al.* (2018b)	MB-MPBR	RSEW, SSEW	COD (30–100)	NO_x (8–9.9)	PO_4^{3-} (12–9.3)	Native microalgae-bacteria consortia	L	PVDF, HF, 0.1 μm	0.043	20	12 h/12 h (8,000 lux)	Air, 0.04% CO_2	26	7.0
González *et al.* (2017)	MB-MPBR	RSEW	COD (124)	46	6	Native microalgae-bacteria consortia	P	PVDF, HF, 0.04 μm	0.9	12	Outdoor (150–224 W/m^2)	NA	Outdoor (18.9)	7.7
Derakhshan *et al.* (2019)	B-MB-MPBR, MB-MPBR	SSEW	COD (30–90)	5	1	Microalgae-bacteria consortia	L	PVDF, HF, 0.1 μm	0.043	20	12 h/12 h (8,500 lux)	Air, 0.04% CO_2	33	7.0
Fortunato *et al.* (2020)	MPBR	SSEW	–	60	10	*Chlorella vulgaris*	L	PVDF, HF, 0.016 μm	3.7·10–3	20	130 μmol/m^2 s	Air 30 L/h	25	7.0–8.0
Choi (2015)	MPBR	RPEW	COD (209.9)	40.0	9.2	*Chlorella vulgaris*	L	PES, 0.2 μm	0.2	8	16 h/8 h (270–310 μE/m^2 s)	Air 0.5 L/min, CO_2	25	7.2
Zhang *et al.* (2020)	MB-MPBR	SMW	COD (440.3)	36.9–46.5	38–9.5	*Chlorella Vulgaris*-activated sludge	L	PVDF, FS, 0.1 μm	0.03	6.8; 10.6	8,400 lux	Air 3.75 L/min, 0.05% CO_2	26.9	7.3
González-Camejo *et al.* (2020a)	MB-MPBR	RSEW	COD (71)	45.0	4.7	Native microalgae-bacteria consortia (dominated by *Chlorella* sp.)	P	PVDF, HF, 0.03 μm	2 × 3.4	15–26	Outdoor + artificial LED lamps (281–344 μmol/m^2 s)	Air, CO_2 (pH control)	Outdoor + cooling system (23.9–25.5)	7.5
Parakh *et al.* (2020)	MPBR+ Settler	SSEW	-	14	0.65	*Graesiella emersoni*	L	PVDF, 0.1 μm	0.0588	NA	14 W	1.5 L/min, 5% CO_2	NA	6.5–7.5
Honda *et al.* (2017)	MPBR	SSEW	TOC (5)	15	0.3	*Chlorella vulgaris* NIES-2170	L	PVDF, HF, 0.1 μm	0.085	NA	20 W/m^2	Air, 1% CO_2	24	NA
Praveen *et al.* (2019)	MPBR	SSEW	–	21	6	*Scenedesmus obliquus* FACHB-417	L	PVDF, FS	0.0308	2.4	130 μmol/m^2 s	Air, 3% CO_2	NA	6.5–7.5

(*Continued.*)

Table 7 | Continued

ID	Process[a]	Feedwater[b]	C[c] (mg/L)	TN (mg/L)	TP (mg/L)	Microbial species	Scale[d]	Membrane[e]	Area (m^2)	Flux (L/m^2 h)	Light	Aeration	Temp (°C)	pH
Noguchi *et al.* (2017)	MPBR	SADS	TOC (0.66)	85.4	23.1	*Chlorella vulgaris* NIES-2170	L	HF, 0.1 μm	0.085	NA	24 h/9 h (6 W/m^2)	–	21.7	7.0–8.0
Lee *et al.* (2018)	MPBR	RISEW	TOC (26.5)	41.6	0.7	*Botryococcus braunii*	L	PVDF, 0.5 μm	$2.81 \cdot 10^{-3}$	2.4; 3; 4	220 μE/m^2 s	6 L/min	25	NA
González-Camejo *et al.* (2018)	MB-MPBR	RSEW	COD (72)	40–80	4–10	Native microalgae-bacteria consortia (dominated by *Chlorella* sp. and *Scenedesmus* sp.)	P	PVDF, HF, 0.03 μm	2 × 3.4	NA	Outdoor (119–357 μmol/m^2 s) +artificial LED lamps (300 μmol/m^2 s)	0.09 vvm, CO_2 (pH control)	16–28	7.5
Azizi *et al.* (2021a)	MPBR	SSEW	–	NO_3^- (83)	PO_4^{3-} (9)	*Chlorella vulgaris*	L	0.45 μm	NA	18	24 h/0 h; 16 h/8 h; 12 h/12 h (100; 300 μmol/m^2 s)	Air, 0.04% CO_2	25	NA
Derakhshan *et al.* (2018a)	B-MB-MPBR	RSEW	COD (59)	NO_x (11)	PO_4^{3-} (10)	Native microalgae-bacteria consortia	L	PVDF, HF, 0.1 μm	0.043	20	12 h/12 h (100 μmol/m^2 s)	4–5 L/min, 0.04% CO_2	26	NA
Gao *et al.* (2021)	MPBR	RSEW	TOC (107)	48.4	4.23	*Chlorella pyrenoidosa* FACHB-5	L	PVDF, HF, 0.1 μm	0.05	NA	82.4–90.6 μmol/m^2 s	40 mL/min, CO_2	30	7.3
Novoa *et al.* (2020)	MPBR	SSEW	–	65	10	*Chlorella vulgaris* UTEX 259	L	PVDF, HF, 0.018 μm	NA	10	130 μmol/m^2 s	30 L/h	25	7.0–8.0
Solmaz & Işık (2019)a, 2019b)	MB-MPBR	RSEW	BOD (12)	5.2	0.6	Native microalgae-bacteria consortia	L	PVDF, HF, 0.45 μm	NA	20	12 h/12 h (6,000 lux)	5 L/min	23	7.5–9.0
Lau *et al.* (2019)	SB-MPBR	RSEW	NA	20–21	2.25	*Staurastrum* sp.	L	PVDF, FS, 0.16 μm	0.02	40	1,000 lux	3.5 L/min	20	NA
Wang *et al.* (2020)	O-MPBR	SSEW	Glucose (50)	NH_4Cl (30)	K_2HPO_4 (21.4) + KH_2PO_4 (10.6)	*Chlorella vulgaris* UTEX 395, *Scenedesmus* sp. HTB1	L	HF	2.3	NA	16 h/8 h (100 μE/m^2 s)	20% CO_2/N_2 (pH control)	20	NA
Solmaz & Işık (2020)	MB-MPBR	SSEW	COD (32.9)	18.0	8.8	Microalgae-bacteria consortia	L	PVDF, HF, 0.45 μm	NA	20	12 h/12 h (6,000 lux)	5 L/min	23	6.4–7.5
Dalaei *et al.* (2020)	PAnMBR	SPEW	COD (430) + Ethanol (200; 300)	43	6.5	Native purple phototrophic bacteria	L	FS, 0.45 μm	0.12	1.9	IR light (3; 1.4 W/m^2)	–	22	7.3
Dalaei *et al.* (2019)	PAnMBR	SPEW	COD (370) + Ethanol (285; 290; 300; 310; 400)	48–56	6.6–8.2	Native purple phototrophic bacteria	L	FS, 0.45 μm	0.12	1.9	IR light (50 W/m^2)	–	22; 11	7.2
Solmaz & Işik (2019)a, 2019b)	MB-MPBR	SSEW	COD (32.9)	18.4	8.8	Microalgae-bacteria consortia	L	PVDF, HF, 0.45 μm	NA	20	12 h/12 h (6,000 lux)	5 L/min	23	6.4–8.2

Keramati *et al.* (2021)	MPBR	RISEW	COD (67)	NO_3^- (49)	PO_4^{3-} (36)	*Chlorella vulgaris*	L	FS, 0.4 μm	NA	20	LED flashing light (1 Hz; 1,000 Hz) (200 μmol/m^2 s)	7 L/min	NA	7.0–8.0
Lee *et al.* (2020)	MPBR	SISEW	TOC (530)	183	15	*Botryococcus braunii* UTEX 2441	L	PVDF, HF, 0.5 um	$2.81{\cdot}10^{-4}$	2.4; 3; 4	24 h/0 h; 12/12 h (150 μmol E/m^2 s)	NA	30	NA
Wang *et al.* (2019)	B-MB-MPBR	RIW+ RPEW	SCOD (1066)	156.3	9.7	Native microalgae-bacteria consortia	L	PVDF, HF, 0.04 μm	1	NA	200–250 μmol/m^2 s	4 L/min	NA	NA
Zhang *et al.* (2021)	MB-MPBR	SMW	COD (440.3)	36.9–46.5	3.8–9.5	*Chlorella vulgaris*-activated sludge	L	PVDF, FS, 0.1 μm	0.03	6.8; 10.6	8,400 lux	3.75 L/min, 0.05% CO_2	26.9	7.3
Spennati *et al.* (2021)	MPBR	RIW	COD (119.3)	NA	NA	*Chlorella vulgaris* CCAP 211, *Arthrospira platensis* UTEX 1926	L	NA	NA	NA	60 μmol/m^2 s	NA	23–25	6.3–7.9
Cheng *et al.* (2021)	B-MPBR	SIW	COD (1025)	N-NH_3 (98.4)	K_2HPO_4 (25)	*Rhodopuesdomonas pulstris*	L	GO/PSF composite	0.05	24.1	300 lux	1.5 m^3/m^2 h	25	7.5

[a]A-MPBR, airlift membrane photobioreactor; B-MB-MPBR, biofilm microalgal-bacterial membrane photobioreactor; MB-MPBR, microalgal-bacterial membrane photobioreactor; MPBR, membrane photobioreactor; O-MPBR, osmotic membrane photobioreactor; PAnMBR, photo-anaerobic membrane bioreactor; SB-MPBR, sequencing batch membrane photobioreactor.

[b]SSEW, synthetic secondary effluent wastewater; SSALW, synthetic saline wastewater; SPEW, synthetic primary effluent wastewater; SMW, synthetic municipal wastewater; SIW, synthetic industrial wastewater; SISEW, synthetic industrial secondary effluent wastewater; SADS, synthetic anaerobic digestion supernatant; RSEW, real secondary effluent wastewater; RPEW, real primary effluent wastewater; RIW, real industrial wastewater; RISEW, real industrial secondary effluent wastewater.

[c]BOD, biological oxygen demand; COD, chemical oxygen demand; SCOD, soluble chemical oxygen demand; TOC, total organic carbon.

[d]L, laboratory; P, pilot.

[e]DM, dynamic membrane; MF, microfiltration; PSF, polysulfone; PVDF, polyvinylidene fluoride; TFC, thin film composite.

NA, not available.

Table 8 | Operating performance of membrane photobioreactors

ID	HRT (day)	SRT (day)	PBR type	Biomass concentration (g/L)	Productivity (mg/L day)	TN removal (%)	TP removal (%)
Gao *et al.* (2016a)	1	NA	Bubble column	0.44–1.1	42.6	86.1	82.7
Tan *et al.* (2014)	–	NA	Airlift	Summer (2.05); winter (0.86); spring (1.97); autumn (1.98)	Summer (0.63); winter (0.14); spring (0.33); autumn (0.51)	Summer (≈ 83); winter (≈ 40); spring (≈ 67); autumn (≈ 75)	Summer (≈ 94); winter (≈56); spring (≈ 96); autumn (≈ 94)
Marbelia *et al.* (2014)	1; 1.4; 2; 2.5; 3.3; 5	5xHRT	Bubble column	1 (≈ 0.2); 1.4 (≈ 0.3); 2 (≈ 0.6); 2.5 (≈ 0.6); 3.3 (≈ 0.4); 5 (≈ 0.4)[a]	1 (≈ 0.03); 1.4 (≈ 0.04);2 (≈ 0.06); 2.5 (≈ 0.04); 3.3 (≈ 0.02); 5 (≈ 0.02)[a]	2 (25); 2.5 (50); 3.3 (80); 5 (100)[a]	2 (50); 2.5 (50); 3.3 (80); 5 (100)[a]
Chitapornpan *et al.* (2013)	10	NA	Rectangular	≈ 1	8.6–12.9	NA	NA
Praveen *et al.* (2018)	3	> 200	Bubble column	0.11–5	49.6–167.0	NA	NA
Singh & Thomas (2012)	1.6	NA	Flat panel	$1.93 \cdot 10^6$ cells/mL	NA	NO_3^- (30–40), NO_2^- (70–80)	PO_4^{3-} (45–70)
Gao *et al.* (2016b)	2	NA	Bubble column	1.8	50.7	≈ 92	≈ 85
Praveen & Loh (2016)	2; 3; 4	Without purge	Rectangular	30–331	NA	N-NH_4^+ (36–87), N-NO_3^- (45–81)	75–87
Zhen-Feng *et al.* (2011)	0.46–0.9	NA	Bubble column	0.14–0.22	NA	< 10–46	< 10–100
Praveen *et al.* (2016)	1; 1.5; 2	Without purge	Rectangular	FO (0.28 g/L); MF (0.23 g/L)	NA	MF (84–97); FO (92–99)	MF (28–47); FO (100)
Sheng *et al.* (2017)	2; 4; 8	60	Rectangular	2 (0.6 g/L); 4 (0.7 g/L); 8 (1.0 g/L)[a]	2 (9.7 mg/L day); 4 (11.2 mg/L day); 8(16.7 mg/L day)[a]	2 (82.8); 4 (96.0); 8 (90.3)[a]	2 (35.7); 4 (70.0); 8 (44.3)[a]
Peng *et al.* (2020)	1; 2	Without purge	Bubble column	1 (1.5 g/L); 2 (1.0 g/L)[a]	1 (22.0 mg/L day); 2 (14.0 mg/L day)[a]	1 (98.1); 2 (94.2)[a]	1 (95.3); 2 (95.6)[a]
Shi *et al.* (2018)	0.5	NA	Flat panel	$4.5–5.5 \cdot 10^6$ cell/mL	NA	NA	NA
Boonchai & Seo (2015)	2	NA	Bubble column	0.2–1.2	55	66.5	94.5
Luo *et al.* (2018)	1; 4	9; 18; 30	Flat panel	1/9 (0.47);1/18 (0.91); 1/30 (1.22); 4/30 (0.85)[b]	1/9 (52);1/18 (51); 1/30 (41); 4/30 (28)[b]	1/9 (31);1/18 (36); 1/30 (32); 4/30 (84)[b]	1/9 (30); 1/18 (31); 1/30 (25); 4/30 (80)[b]
González-Camejo *et al.* (2020b)	1.25	2, 2.5; 4.5	Flat panel	2 (≈ 0.350 g VSS/L); 2.5 (0.347 g VSS/L); 4.5 (0.486 g VSS/L)[c]	2 (136 mg VSS/L day); 2.5 (139 mg VSS/L day); 4.5 (108 mg VSS/L day)[c]	2 (14.1 mg N/L day); 2.5 (19.7 mg N/L day); 4.5 (14.5 mg N/L day)[c]	NA
Viruela *et al.* (2018)	13.1–31.5 g N/day	4.5; 8; 9	Flat panel	NA	4.5 (66 mg VSS/L day)	4.5 (7.7 mg N/L day)	4.5 (2.2 mg P/L day)

(*Continued.*)

Table 8 | Continued

ID	HRT (day)	SRT (day)	PBR type	Biomass concentration (g/L)	Productivity (mg/L day)	TN removal (%)	TP removal (%)
Gao *et al.* (2019)	2	NA	Bubble column	*Chlorella vulgaris* (1.84); *Scenedesmus obliquus* (1.72)	*Chlorella vulgaris* (96.3); *Scenedesmus obliquus* (88.8)	NA	NA
Chitapornpan *et al.* (2012)	10	NA	Rectangular	1.0	12.9	NA	NA
Lu *et al.* (2021)	2; 3	10; 20; 40	Bubble column	2 (0.25–0.7); 3 (0.55–0.9)[c]	2/40 (10.9); 2/20 (28.3); 2/10 (NA); 3/40 (17.1); 3/20 (35.9)[b]	2/40 (26.2); 2/20 (25.6); 2/10 (34.6); 3/40 (44.6); 3/20 (42.3); 3/10 (40.8)[b]	2/40 (66,3); 2/20 (53,7); 2/10 (41,7); 3/40 (77.4); 3/20 (69.2); 3/10 (54.5)[b]
Derakhshan *et al.* (2018b)	0.25; 0.5; 1	NA	Bubble column	6	NA	> 93.7%	> 94.4%
González *et al.* (2017)	0.21	Without purge	Bubble column	1.1	37	39	21
Derakhshan *et al.* (2019)	0.17; 0.33; 0.5	NA	Bubble column	HMPBR (6); MPBR (4)	NA	HMPBR 0.5 (98); MPBR 0.5 (85)	HMPBR 0.5 (98); MPBR 0.5 (98)
Fortunato *et al.* (2020)	0.5	NA	Bubble column	0.5	NA	NA	NA
Choi (2015)	3.4	NA	Flat panel	1.12	0.00253	96.4	92.8
Zhang *et al.* (2020)	2; 3	20	Bubble column	2 (2.33–2.55); 3 (1.67–2.40)[a]	2 (116.5–127.5); 3 (83.5–120.0)[a]	2 (78.6–81.7); 3 (72.5–99.5)[a]	2 (45.4–99.5); 3 (61.8–99.2)[a]
González-Camejo *et al.* (2020a)	1.25; 1.5	3; 4.5	Flat panel	1.25/3 (531–731 mg VSS/L); 1.5/3 (823 mg VSS/L); 1.5/4.5 (801 mg VSS/L)[b]	1.5/3 (258 mg VSS/L day)[b]	80–85	90–99
Parakh *et al.* (2020)	1	5–25	Bubble column	0.6–3.4 (suspension); 16.1–31.1 (settled)	130–260	90–92	99–100
Honda *et al.* (2017)	0.33; 1	12	Flat panel	0.314–0.872	26.2–39.0	65.9–70.0	82.5–96.8
Praveen *et al.* (2019)	2	2; 2.5; 5; 10; 20; 30; 50; 350	Bubble column	2 (0.54); 2.5 (0.78); 5 (1.07); 10 (1.97); 20 (1.98); 30 (1.90); 50 (1.86); 350 (2.03)[c]	50–270	94.9–97.1	71.4–78.2
Noguchi *et al.* (2017)	1	12; 56	Rectangular	0.4	5.58	89	90
Lee *et al.* (2018)	3; 4; 5	14;15; 16	Cylindrical	3 (3.5); 4 (3); 5 (3.1)	201	96	85
González-Camejo *et al.* (2018)	2; 2,5; 3; 8; 14	4,5; 8; 14	Flat Panel	0.2–0.4 g VSS/L	2.5/4.5 (72 mg VSS/L day)	2.5/4.5 (12.5 m g N/L day)	2.5/4.5 (1.5 mg P/L day)

(*Continued.*)

Table 8 | Continued

ID	HRT (day)	SRT (day)	PBR type	Biomass concentration (g/L)	Productivity (mg/L day)	TN removal (%)	TP removal (%)
Azizi *et al.* (2021a)	1	Without purge	Flat Plate	NA	6–18	40–60	20–45
Derakhshan *et al.* (2018b)	0.125; 0.25; 0.5; 1	Without purge	Bubble column	5	0.17–0.73 g SS/g COD	NA	NA
Gao *et al.* (2021)	4	20	Cylindrical	1.7–1.9	91.1	8.4 mg N/L day	0.9 mg P/L day
Novoa *et al.* (2020)	0.5; 1; 1.5	Without purge	Bubble column	0.5 (1.7); 1 (1.4); 1.5 (0.8)[a]	0.5 (90); 1 (61.8)[a]	NA	NA
Solmaz & Işık (2019a, 2019b)	1	3	Bubble column	0.110	37	5.55 mg N/L day	0.4 mg P/L day
Lau *et al.* (2019)	4	150	NA	0.6	40–30	50	10
Wang *et al.* (2020)	1.7; 3.3; 6.7	9.4; 17.8; 25.3	NA	0.82	NA	≈ 100%	≈ 100%
Solmaz & Işık (2020)	1; 2; 2.5; 3	3	Bubble column	0.19–0.35	64–118	30.3–46.8	4.6–5.9
Dalaei *et al.* (2020)	0.375; 0.75; 1.5	5	Flat panel	0.29–1.25	NA	44–86	69–91
Dalaei *et al.* (2019)	0.375; 0.75; 1.5	3	Flat panel	0.4–1.6	NA	40–91	83–89
Solmaz & Işik (2019a, 2019b)	1	2; 3; 6; 12; 24	Bubble column	3 (0.35); 6 (0.35); 12 (0.61); 24 (1.03)[c]	3 (118); 6 (61); 12 (51); 24 (43)[c]	3 (5.55 mg/L day); 6 (4.02 mg/L day); 12 (5.05 mg/L day); 24 (4.88 mg/L day)[c]	3 (0.4 mg/L day); 6 (0.29 mg/L day); 12 (1.36 mg/L day); 24 (1.61 mg/L day)[c]
Keramati *et al.* (2021)	NA	NA	Flat panel	1.4–2–5	15–30	68–97	47–70
Lee *et al.* (2020)	3; 4; 5	15	Rectangular	0.66–2.75	NA	77–72	98–96
Wang *et al.* (2019)	5	15	NA	0.5–1.9	NA	69–99	NA
Zhang *et al.* (2021)	2; 3	20	Bubble column	1.6–2.55	NA	72.5–99.5	45.4–99.2
Spennati *et al.* (2021)	1.4; 2; 4.6	NA	Bubble column	0.82–6.10	39–240	NA	NA
Cheng *et al.* (2021)	16.7	30	Rectangular	NA	NA	84	NA

[a]Data expressed as: HTR (value).
[b]Data expressed as: HTR/SRT (value).
[c]Data expressed as: SRT (value).

growth is favoured by higher irradiation in the photobioreactor, the highest productivity is obtained at low SRTs (2–3 days), where lower microalgae concentrations (<1 g/L) are obtained (Praveen *et al.* 2019; Parakh *et al.* 2020).

3.7.3. Process configuration

The most studied configuration is MPBR with pure microalgae cultures, which represent 46% of papers (Table 7). These studies focus mainly on the analysis of biomass productivity and nutrient removal capacity (Table 8). The application of MPBRs to real secondary effluents with an appreciable amount of carbonaceous matter (COD = 30–100 mg/L) or untreated wastewater (COD > 400 mg/L) has led to the development of microalgal-bacterial photobioreactors (MB-MPBRs), where synergies can be established between different microorganisms. In these studies, which represent 26% of the analysed works, native consortia of microalgae and bacteria are developed, which adapt to the imposed conditions. In laboratory-scale studies, a 12 h/12 h photoperiod is usually applied, studying the behaviour of this configuration for a range of HRT and SRT conditions (1–3 and 2–24 days, respectively) similar to that studied for MPBRs (Solmaz & Işik 2019a, 2019b; Solmaz & Işık 2020). Comparable results in terms of productivity and nutrient removal have been obtained with this process. In addition, studies at pilot scale and under ambient light and temperature conditions have laid the groundwork for larger-scale design (González *et al.* 2017; Viruela *et al.* 2018; González-Camejo *et al.* 2018, 2020a, 2020b). Sustainable operation with adequate nutrient removal efficiencies has been demonstrated for SRTs of 3–4.5 days and HRTs of 1.25–1.5 days. Also, for these conditions, low membrane fouling can be operated at filtration fluxes of 15 L/h m^2 and a specific membrane aeration flow rate of 16–20 Nm^3 air/m^3 permeate (González-Camejo *et al.* 2020a).

The rest of the works analysed (28%) studied other configurations of the technology, including biofilm microalgal-bacterial membrane photobioreactor (B-MP-MPBR), osmotic membrane photobioreactor (O-MPBR), and photo-anaerobic membrane bioreactor (PAnMBR). Derakhshan *et al.* (2018b) and Derakhshan *et al.* (2019) have shown an appreciable increase in COD and nutrient removal from a B-MP-MPBR over an MP-MPBR. In relation to O-MPBR, although removal efficiencies are higher than those obtained in MPBR, so are the total operating costs, which limits the widespread application of this configuration (Praveen *et al.* 2016). Finally, in the case of PAnMBR, its application is limited to industrial or domestic wastewater with high organics (Chitapornpan *et al.* 2012, 2013; González-Camejo *et al.* 2018; Dalaei *et al.* 2020). Although preliminary studies show the potential of this configuration, comparable to conventional treatment, more studies are needed on fundamental aspects of the process, such as the influence of the reactor type on light transmissivity, membrane fouling, or methane production (Dalaei *et al.* 2020).

3.8. Research hotspots and tendencies

Many authors have focused their studies on the application of MPBR in wastewater treatment; however, most have been based on laboratory-scale studies (Liu & Hong 2021). Regarding pilot-scale experiments, these have only been conducted in recent years (González-Camejo *et al.* 2020b; Viruela *et al.* 2021). It should be noted that outdoor cultivation requires an appropriate photobioreactor design for efficient light utilisation. Tested configurations are bubble columns and flat panels, but other photobioreactors should be explored. Another crucial factor requiring consideration is the biomass concentration, as its augmentation is required for reducing harvesting costs. Nevertheless, according to the literature, elevating the biomass concentration can be challenging due to the occurrence of self-shading effects. Consequently, achieving an optimal photobioreactor configuration that effectively addresses this limitation remains a significant and unresolved challenge.

One of the first research hot spots that can be identified is the great number of studies that evaluate the application of this technology with real wastewater in order to reach sound conclusions on the best cultivation conditions depending on the characteristics of the water entering the photobioreactor. Thus, the pilot phase is a key step for the industrial scaling-up of this technology. However, there are practically no studies dedicated to the analysis of the economic viability of the process under real conditions (Li *et al.* 2019).

The control of fouling, a parameter that has been found to be key in the operability of the process, is another possible future research area. Some authors consider that the substances excreted by microalgae are the main causes of fouling (Lee *et al.* 2018), since their composition may contain proteins with a hydrophobic character that can form gel-like structures that block the membrane pores (Novoa *et al.* 2021). However, despite the importance of this parameter in the operability of the process, there are almost no studies devoted to the continuous analysis of fouling and its characterisation. Even though, some authors have pointed out that understanding how fouling occurs in membranes represents one of the greatest challenges in this technology (Novoa *et al.* 2021).

Moreover, although some authors have used MPBRs for the treatment of raw wastewater, the feed to the system has been subjected to centrifugation (de Godos *et al.* 2009b, 2010) or screening and subsequent sedimentation (Godos *et al.* 2009a). This results in the suspended solids content being greatly reduced and only the soluble fraction of carbon, nitrogen and phosphorus being fed to the system. It is widely known that high organic matter loads are counterproductive for microalgae growth and that the turbidity generated by suspended organic matter causes photoinhibition (Wang *et al.* 2016). Consequently, some authors point out that this technology has the potential to be used as a secondary or tertiary wastewater treatment (Nagarajan *et al.* 2020).

Other authors consider that a potential difficulty of this technology is the need for long hydraulic retention times to achieve adequate nutrient removal, namely retention times of 7–10 days as opposed to the less than 1 day that is considered optimal for wastewater treatment (Nagarajan *et al.* 2020). A long HRT means that land availability for the implementation of MPBRs is an obstacle to overcome. Therefore, exploring alternative design and operational strategies to attain elevated microalgal or microalgal-bacterial concentrations within MPBRs emerges as a promising approach. Such strategies hold the potential to enhance the overall performance of these systems, particularly at low HRT.

On the other hand, the biodegradation and bioadsorption of persistent organic pollutants (POPs) are identified by some authors as a future application of the algae-bacteria consortium that can be developed in a membrane photobioreactor (Chan *et al.* 2022). Further studies on the degree of assimilation of these pollutants and the concentrations that are inhibitory to biomass growth are required to establish the best operating conditions.

The utilisation of the biomass generated in the operation of a membrane photobioreactor applied to wastewater treatment may also be a field to be developed in the coming years. A prominent constraint associated with MPBRs lies in the comparatively low biomass productivities reported, which significantly diverge from the yields achieved in conventional closed photobioreactors. Moreover, when considering the up-scaling of this process to accommodate large volumes of wastewater, it is suggested to employ open systems, such as raceways or thin-layer reactors. Through the implementation of such systems, the generated biomass can be effectively harvested for diverse applications, encompassing the utilisation of microalgae-based products as biofertilisers for agriculture and as a valuable resource for biofuels production (Silambarasan *et al.* 2021). Nevertheless, it is essential to acknowledge that the composition of the biomass, and hence its quality, can be influenced by the nature of the wastewater employed. Notably, the presence of heavy metals and a low phosphorus content in the wastewater has been identified as significant drawbacks in this regard (Morillas-España *et al.* 2022). In addition, biomass pyrolysis is presented as a method to produce biofuels from microalgae (Adeniyi *et al.* 2018). Some authors have made progress in this direction by establishing a model for the pyrolysis of biomass from the operation of a laboratory-scale membrane photobioreactor (González *et al.* 2020). In this context, it is crucial to address the issue of high ash content in microalgae to optimise the yields of pyrolysis products (Sotoudehniakarani *et al.* 2019).

Process modelling is another potential future research trend in this field. Indeed, the use of experimental data to make models that include the wide range of variables that influence the process (lighting, temperature, climate influence, microalgae species, type of feed water, etc.) (Li *et al.* 2019) can be a great tool to predict behaviour and design facilities in the future.

4. CONCLUSIONS

MPBR applied to wastewater treatment have proven to be a technology that has attracted growing interest in the scientific community in the last 5 years.

1. Most publications on the topic have been in the field of Environmental Sciences and the Journal Bioresource Technology is the outlet for most of the articles. China has been the country with the most publications; however, the author who has made the greatest contributions to the topic is Spanish and works at the University of Valencia.
2. Temporal analysis of keywords shows the scientific community's increasing interest in the use of this technology for nutrient removal, and the need to control a key parameter, membrane fouling, in order to save costs and improve the operability of the overall process.
3. The future of this technology seems to lie in improving operating conditions to increase the nutrient removal performance of the wastewater and in minimising membrane fouling. All these advances should be studied under real conditions, with pilot-scale experiments. In addition, options must be found for the subsequent use of the biomass obtained in the process to improve overall process performance.

4. This bibliometric review allows any researcher who is interested in this field, to know the most recent advances and the investigations carried out in the application of MPBR in wastewater treatment.

AUTHOR CONTRIBUTIONS

E. S.-M. wrote the original draft, and rendered support in data curation and editing. E. G. visualised, wrote the review and edited the article. A. F. rendered support in the investigation and data curation. O. D. conceptualised the whole article, developed the methodology, investigated the article, and wrote and reviewed the article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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