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Review

Biodesalination Research Trends: A Bibliometric Analysis and Recent Developments

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Abstract: Due to rising population and industrialization, two-thirds of the world's population may suffer water scarcity by 2025. Biodesalination is a promising sustainable practice targeting salt removal from seawater by micro-organisms, using lower energy consumption and resulting in less environmental impact. This study examined the evolution of biodesalination from 2007 to 2022 by applying bibliometric analysis. A scoping review was also conducted through content analysis of biodesalination publications. Using the Scopus database, the research trends, major contributors in the field, and recent advancements were identified. The study investigated a total of 80 peer-reviewed journal articles in the field of biodesalination. Results of the bibliometric analysis revealed that publications peaked in 2022 and citations in 2021, with values of 14 and 473, respectively. Results also revealed that the research trend in biodesalination is leaning towards the use of microbial desalination cells. Furthermore, advancements in the field focused on enhancing the nutrient medium to yield better growth rates for algae and cyanobacteria and improve desalination efficiencies to up to 40%. Other modifications focused on introducing microbial strains with increased salinity tolerance. Finally, an outline of future research potential was presented, focusing on nutrient medium modifications, specifically the substitution of chloride and sodium salts in the medium with nitrate and potassium minerals.

Keywords: biodesalination; biological desalination; microbial desalination; bibliometric analysis

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1. Introduction

Freshwater sources are limited and are being depleted at a fast rate. Due to the rapid increase in population in the last few decades, several continents suffer from water scarcity. This is mainly because of the uneven distribution of water resources worldwide, unsustainable use, management, and water pollution. According to statistics, half a billion people throughout the globe experience severe water shortages all year round [1]. Around two-thirds of the global population faces severe water scarcity for at least a month annually [1]. Similarly, a large population living next to coastal areas consumes desalinated seawater for daily needs. This percentage accumulates to around 1% of the world's population [2]. Desalination is becoming more popular for supplying water demands for domestic and industrial use. However, the process comes at the expense of several environmental impacts from the high energy consumption and brine discharge. Fossil fuel empowers the majority of desalination plants worldwide, contributing to an increase in greenhouse gas emissions (GHG). On the other hand, studies have revealed that approximately 142 million m^3 of brine is produced every day, endangering coastal ecosystems [3,4].Surface water discharge, deep well injection, sewage discharge, evaporation ponds, and land applications are some methods used to dispose of brine from desalination plants [5]. Furthermore, conventional

desalination methods have high capital and operational costs, resulting in substantial financial burdens on countries' economies.

Biodesalination is a promising sustainable practice for desalination. The process is defined as an emerging technology for the selective removal of Na^+ and Cl^- from seawater by micro-organisms such as algae or cyanobacteria [6]. The principle of the process is that sufficient micro-organisms' growth should consume or engulf ions from high-salinity water to provide effective salt removal. Furthermore, biomass is cultivated sustainably, using minimal nutrient input and ambient solar energy. Problems arise when trying to implement biodesalination on a large scale because of the complexity of the process, the need for optimization, and the difficulty of scaling up. In addition, the technology has to prove it can generate economical gains before being mainstreamed. Currently, the research themes in the field of biodesalination are evolving around strain selection, nutrients/minerals requirements, and scaling up.

Despite the growing interest in biodesalination, and the importance of considering aspects such as the different strains and nutrient medium modifications, few review articles discuss these aspects [7,8]. Additionally, no bibliometric analysis has previously been conducted on the topic. Bibliometric analysis is a scientific computer-assisted review process that identifies key research or authors and their relationships by examining all publications on a particular subject or area [9]. In this study, a bibliometric analysis was conducted to extract insights through the processing of large volumes of unstructured data in the field of biodesalination by finding collaborative patterns and investigating the intellectual structure of the topic. The bibliometric analysis would also help map the accumulated scientific knowledge and research themes under the field of biodesalination. Therefore, this study can help researchers in the field of biodesalination identify improvement opportunities, novel ideas, and research gaps [10]. Additionally, this paper includes a scoping review of the recently published peer-reviewed journal articles on biodesalination, which aims to highlight recent advancements in the field of biodesalination, and the research gaps. Finally, the integration of results from the bibliometric analysis and the scoping review identified pertinent improvements in the field. Specifically, the study focused on the following research questions:

RQ 1: When analyzing publications addressing biodesalination, what research trends may be found?

RQ 2: Which countries are leading contributors to biodesalination research?

RQ 3: What are the recent advancements and research gaps in the field of biodesalination?

2. Background

2.1. Mechanisms of Biodesalination

The two processes of biosorption and bioaccumulation for salt removal from a saline environment are involved in biodesalination [7]. The process of quickly bonding ions or molecules to a wet or dry algal surface is known as bioadsorption [11]. It is a metabolically independent and reversible process that occurs on the surface due to the surface characteristics of the adherents with no energy expenditure [11]. Bioaccumulation is an active energy-dependent biological process that occurs in living cells via salt uptake or accumulation; however, it is a slow process [11]. It is a two-step process that starts with fast passive salt adsorption on the outside cell surface and progresses to slow intracellular diffusion [12]. Analyses of biodesalination showed the extent of involvement of the two mechanisms in biodesalination, where bioadsorption's role was dominant at 75% [11].

2.2. Cyanobacteria

Cyanobacteria, which are a blue-green algae, form a group of prokaryotic, autotrophic micro-organisms that contain photosynthetic pigments and can adapt to severe environments due to their terrestrial habitat [6]. The strength of cyanobacteria is that it requires minimal growth requirements and that it can form strong adaptability in toxic environments. Scientists are trying to put these characteristics into use by introducing the strain

in hypersaline and toxic systems. Previous research has shown that cyanobacteria collect intra- or extra-cellular osmolytes in response to ionic stress [6]. They also observed that cyanobacteria transfer Na^+ through diffusion under ionic stress [7].

2.3. Challenges of Biodesalination

Biodesalination presents challenges such as decreasing removal efficiency proportional to time, increased energy consumption during the harvesting stage, and the need for downstream processing of algal biomass to extract products. Algal biodesalination is not an effective desalination method for providing potable water, according to available research [11]. During the development period, biodesalination in the lab showed significant salt removal efficiency, but performance gradually decreased afterward. The efficiency decline becomes more pronounced with time. Furthermore, as the number of dead cells increases, so does the number of salts they discharge into the environment. Due to their small size, negative surface charge, decreased cell density, and exceptionally high moisture content, micro-organisms make cell harvesting a complicated and energy-intensive operation [11]. Finally, the downstream of different byproducts could be adversely impacted by salt and pollutants collected or absorbed on the surface of micro-organisms, depending on the strain.

3. Methodology

The results presented in this paper are based on a bibliometric analysis of articles published between 2007 (date of first publication) and 2022 in biodesalination. Furthermore, the analysis helped identify the research contributions from various countries, institutions, and scholars.

3.1. Data Collection

Scopus, Web of Science (WOS), and Google Scholar were the candidate databases to conduct the bibliometric analysis. After carefully examining the three databases, Scopus was selected because it contained more scientific publications related to biodesalination. Scopus also has access to a broad range of high-ranking journals, which helped form more realistic research trends. In total, 80 research articles were retrieved from 2007–2022 after carefully scoping the Scopus database [6,13–91]. The following research queries were used for data collection, i.e., "Biodesalination" OR "Bio-desalination" OR "Biological Desalination" OR "Microbial Desalination". The advanced search form in Scopus was used, as the research queries were investigated in the database as "Title, abstract, or author-specified keywords". As this paper aimed to examine the current research situation and trends, only peer-reviewed research journal articles were used for the analysis.

3.2. Data Analysis

This paper considered both categories of bibliometric analysis for the evaluation: performance analysis and science mapping. The measures are further explained in the following subsections.

3.2.1. Performance Analysis

In this type of analysis, research constituents were evaluated, and their contribution to a particular field was measured according to background or profile. Three performance analysis metrics were considered: publication-related, citation-related, and citation-and-publication-related. The publication-related metrics evaluated were:

1. Total publications (TP);
2. Productivity per active publication year (PAY); and

$$\mathrm{PAY} = \frac{\mathrm{TP}}{\mathrm{NAY}}, \tag{1}$$

where: PAY—productivity per active publication year, TP—total publications, and NAY—number of active years of research.

3. Number of contributing authors (NCA).

The measures evaluated from the citation-related and citation-and-publication-related metrics were the total citations (TC) and the proportion of cited publications (PCP), respectively. The equation used to evaluate the PCP is:

$$PCP = \frac{NCP}{TP} \quad (2)$$

where: PCP—proportion of cited publications, NCP—number of cited publications, and TP—total publications.

3.2.2. Science Mapping

For the science mapping approach, five categories were analyzed to examine the relationships between publications. This type of analysis investigated the interactions of research constituents. It is concerned with the intellectual exchanges and structural linkages that exist between research elements. The categories analyzed were as follows:

1. Co-word analysis;
2. Citation analysis;
3. Co-citation analysis; and
4. Co-authorship analysis.

3.2.3. Software Selection

The analysis was performed using "VOSviewer 1.16.18" and "Microsoft Excel 16.66.1"; both providing visualization and quantitative results. Both software provide tools for the construction and visualization of bibliometric networks.

3.2.4. Content Analysis

The results obtained from the bibliometric analysis were used to determine the research trends in the field of biodesalination and map the intellectual structure of authors, organizations, and countries. The results were also used to discover and highlight the recent advancements and research gaps in the field of biodesalination. Figure 1 below illustrates the framework for the study's analysis.

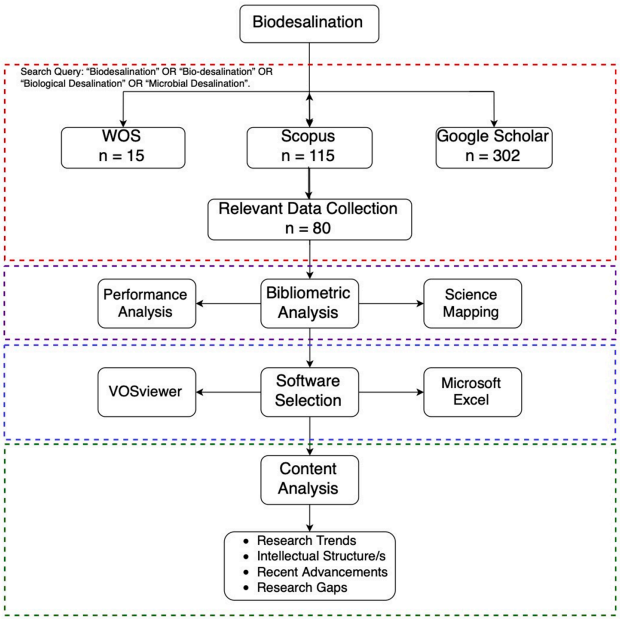

Figure 1. A framework of analysis of the study.

4. Results of the Bibliometric Analysis

4.1. Publication Trends

This section answers part of the first research question, uncovering the trends of publications and citations on biodesalination. The first measure evaluated was the annual TP, which serves as a metric for productivity. The first research article on the topic of biodesalination was dated 2007, as shown in Figure 2.

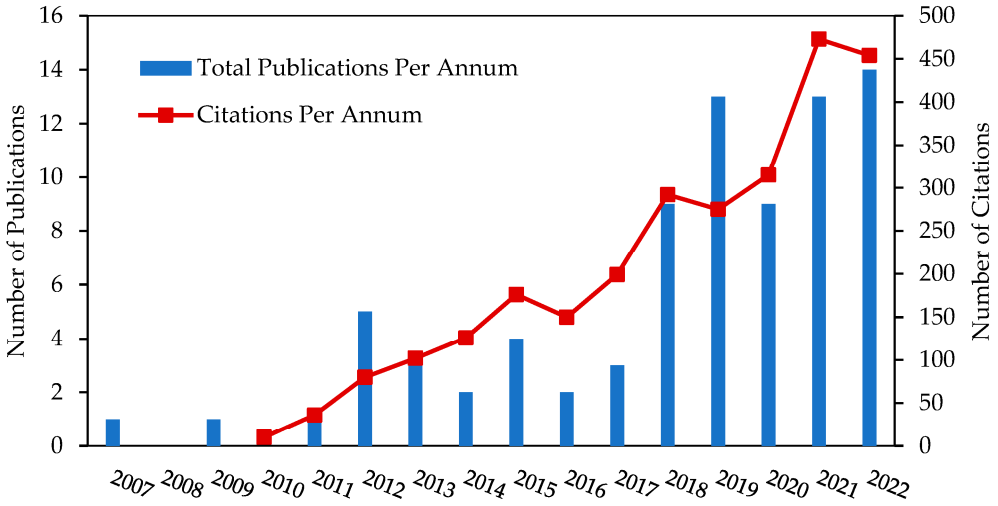

Figure 2. Annual publications and citations on the topic of biodesalination.

The citation trend of the articles included in the database in the same interval is represented by the line graph in Figure 2. It was observed that although the number of articles published annually fluctuated, there was an overall increasing trend in articles published on biodesalination. The most significant increase was observed between 2016 and 2019, with only two publications in 2016 and 13 in 2019, showing an annual growth of 86.63%. Interestingly, this was followed by a decrease of 30.77% between 2019 and 2020. The sudden decline in articles during the year 2020 could be due to the lockdown and the SARS-CoV-2 virus pandemic, which could have halted laboratory research activities [92]. The year 2022 recorded peak publications, with 14 publications before the end of the year, leaving the prospect for more articles to be published. The increasing trend in publications of biodesalination was attributed to the interest and advancements in microbial desalination technologies in the last few years.

Similarly, an increasing trend was observed for citations, with a peak of 473 in 2021. The citation overview indicated that biodesalination is an emerging topic, especially with the few publications available.

The database of all articles considered in this analysis (n = 80) was published in a total of 47 journals. Table 1 lists the journals that hosted the maximum number of articles published on the topic. The top two journals (*Desalination* and *Bioresource Technology*) with the highest publications count were ranked as Quartile 1 in Scopus [93].

Table 1. Top five journals with published documents.

Rank	Journal	Total Publications (TP)
1	*Desalination*	17
2	*Bioresource Technology*	5
3	*Desalination and Water Treatment*	4
4	*Journal of Ecological Engineering*	3
5	*Chemical Engineering Journal*	3

China was identified as the top country publishing the most articles, with 19, representing approximately 24% of the database. The United States of America (U.S.A.) followed

with 16 documents, approximating 20% of the database. India, which introduced the first article in the field of biodesalination in 2007, ranked third with a total of 13 publications, approximating 16% of the database.

4.2. Research Productivity

PAY measure is calculated by dividing the TP by the NAY. The productivity per active year of publication on the topic of biodesalination can be calculated as follows:

$$\text{PAY} = \frac{\text{TP}}{\text{NAY}} = \frac{80}{14} = 5.71 \quad (3)$$

This PAY value of around six publications per active year denotes very low productivity in the field. A recent bibliometric analysis on desalination, spanning 54 years, approximated a PAY value of around 270 [94]. Correlating the two analyses, biodesalination publications account for 2% of desalination publications, which shows that more investigations are needed in the field of biodesalination.

4.3. Emerging and Common Research Keywords

Keywords are nouns or phrases that reflect the core content of the publication. The database of considered articles (n = 80) shows that a total of 138 keywords were included after combining similar nouns and phrases. In the co-word analysis, keywords were studied using VOSviewer, where a link refers to a co-occurrence connection between two keywords. Each formed link has a strength represented by a positive numerical number. The stronger the link, the greater the value. In this study, the co-occurrence threshold of the keywords was set as 1. This measure is important for examining the study field and determining what is gaining particular attention over time. The results of this analysis are shown in Table 2, where microbial desalination cell (MDC) was identified as the most occurring author's keyword with the strongest link. This is not surprising since MDCs were the first technique to be proposed in the field of biodesalination [89]. Interestingly, three keywords were similarly ranked and with similar link strengths; namely, Cyanobacteria, Algae, and Biodesalination. This signifies the neutral/zero energy demand process of salt removal by application of different strains of micro-organisms.

Table 2. The total link strength of the top 15 occurrence keywords.

Rank	Keywords	Occurrences	Total Link Strength
1	Microbial desalination cell	30	108
2	Desalination	27	104
3	Wastewater treatment	21	92
4	Cyanobacteria	19	86
5	Algae	19	74
6	Biodesalination	19	71
7	Salinity	16	69
8	Energy	12	56
9	Bioelectricity	11	46
10	Brackish water	9	34
11	Microbial fuel cell	9	32
12	Biocathode	8	30
13	Microalgae	6	23
14	Seawater desalination	5	22
15	Bio-electrochemical system	5	19

A visualization map for co-keyword analysis was created using VOSviewer software, as shown in Figure 3. The circles' size represents the occurrence frequency of each keyword, and the curved lines show the connection between the keywords indicating the repetition in the different articles. Figure 3 shows links between microbial desalination cells, microbial fuel cells, and power generation. MDCs are modified microbial fuel cells (MFCs) that

produce higher electric generation and record better salt removal efficiencies. In addition, MDC studies revealed that salinity removal efficiency increases with increasing salt concentrations in solutions compared to MFCs [95]. However, their energy production is low, necessitating the need to further enhance the power density to improve their functional capacity. Correlation between the keywords can also be attributed to endeavors of reducing internal resistances of the MDCs that result from the desalination compartment.

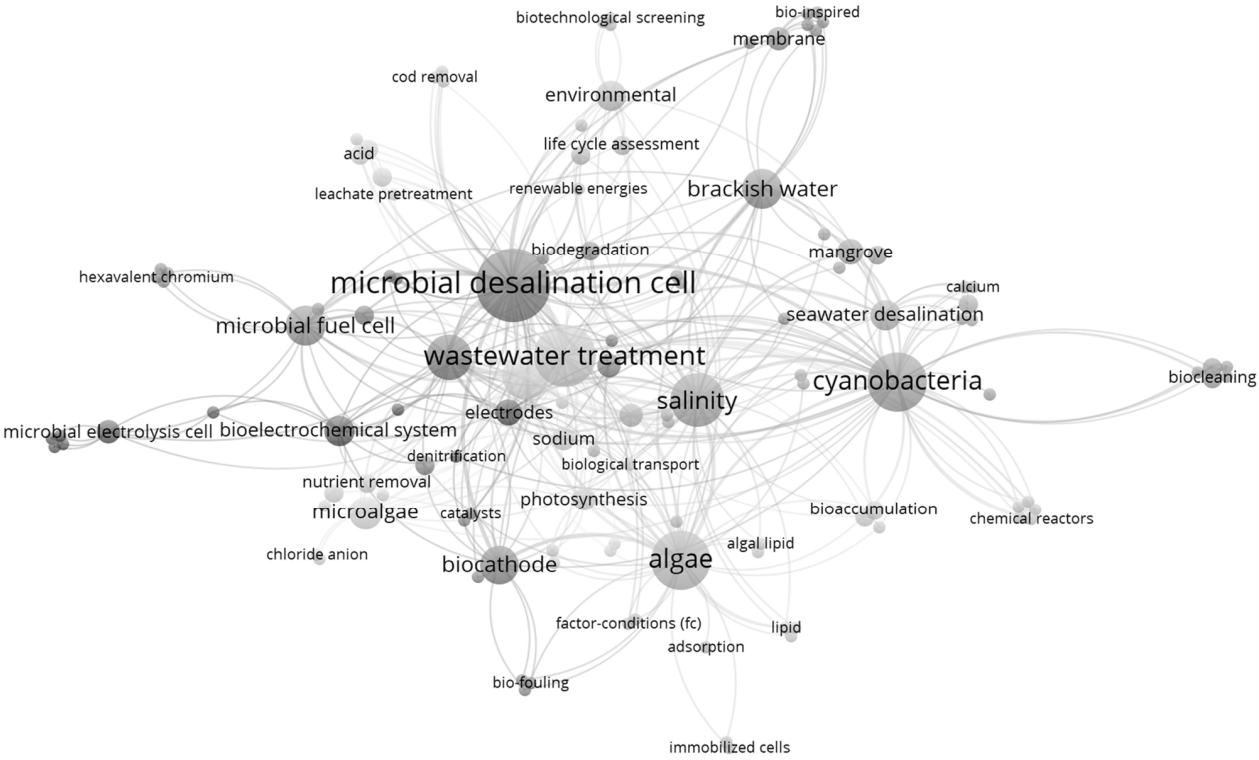

Figure 3. Co-keyword network visualization on biodesalination research. Keywords related to desalination were removed for figure clarity ('Biodesalination' and 'Desalination').

Another correlation was observed between microbial desalination cells, renewable energies, life cycle assessment, and environmental impacts. This reveals that MDCs are studied extensively. Studies reveal that both the manufacture and operation of MDCs have significant environmental consequences, with the former accounting for 22.7% and the latter for 58.7% of the global warming potential during the whole life cycle [63]. In the operation phase, a significant percentage of the global warming potential would decrease if renewable energy was integrated. Several studies in the study's database experimented integration of renewable energy in this technique.

Wastewater treatment recorded various connections. This could be related to the trials performed to supply the nutrient requirements of different strains of micro-organisms from wastewater for biodesalination. Those applications included industrial and municipal wastewater treatment, where micro-organisms gained increased salt tolerance ability in some cases. Furthermore, cyanobacteria and microalgae keywords appeared not to be correlated with energy, as the new approach of biodesalination provides a salt removal process with neutral/zero energy demands.

For further investigation of trends in the use of keywords in biodesalination, a threshold of five occurrences was set, which resulted in 16 keywords. Only one keyword—biocathode—showed a declining trend, whereas all other keywords displayed an increasing trend. It can be predicted that the reduction in biocathode research trend might be shifting to another new domain. The decline could also be related to the startup of biocathodes, which is a challenging and time-consuming operation since the micro-organisms' ability to obtain energy is inevitably constrained by the low electrode potentials [96]. Additionally, it

is yet unknown which material is better for biocathodes. Moreover, 8 of the 16 keywords were analyzed in Figure 4 for their growth trend during four-year intervals: 2007–2010, 2011–2014, 2015–2018, and 2019–2022. 'Algae', 'cyanobacteria', 'salinity', and 'energy' showed significantly increasing trends of occurrences. This indicates the focus on achieving higher salinity removal efficiencies of biodesalination using different strains of algae and cyanobacteria while minimizing the energy needed for the process. The first three keywords showed similar growing behavior in Figure 4, indicating their strong correlation. The association of their growth trends is denoted by salinity being a controlling factor of cell growth and functionality. Another relation was observed between MDC and bioelectricity which indicates investigations of the potentials of bioelectricity in the technique. From Figure 4, it can be observed that the impact of MFCs has not advanced in biodesalination studies compared to algae and cyanobacteria. Additionally, publications from the last interval included keywords such as 'resource recovery', 'environmental impacts', and 'reverse osmosis'. The keywords denote an increasing trend of research revolving around sustainable methods of performing biodesalination while reducing the environmental impacts of the process.

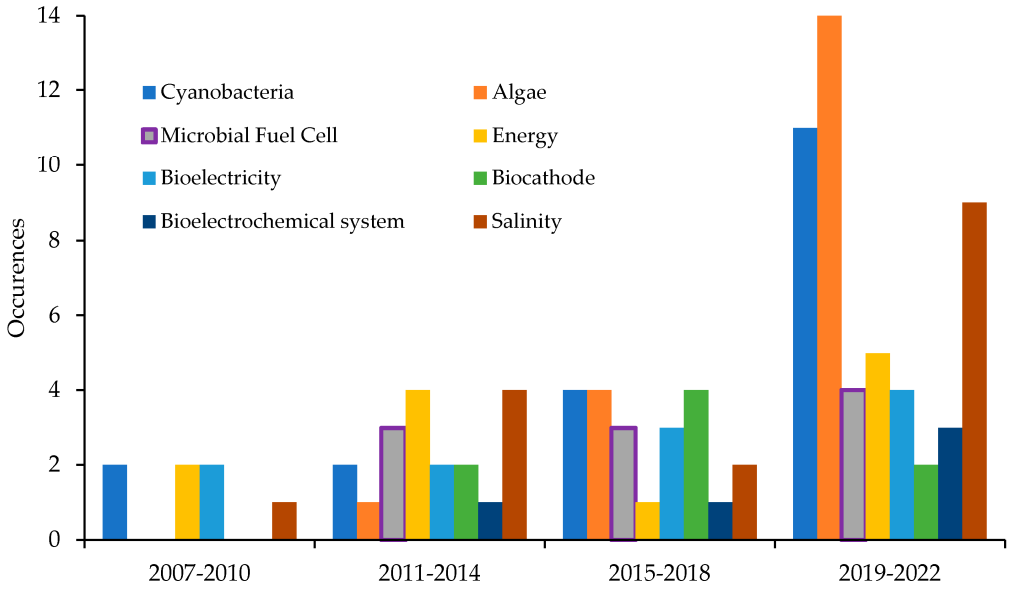

Figure 4. Analysis of significant keywords in the field of biodesalination.

4.4. Analysis of Citations and Authorship in Biodesalination

In the TC analysis, the most citations were recorded for Logan B.E. from Pennsylvania State University, with a total of 811 citations from two publications. Kang Xiao, from the University of Chinese Academy of Sciences, recorded the highest value for citations per publication (CPP). This measure was not examined in detail because of co-authorships between several authors in the most cited publications, resulting in similar citation counts.

The research articles in the database were also analyzed for their citations using global citations. The article with the first rank in Table 3 laid the foundation for biodesalination using MDCs, which explains its importance and citation count. In the following table, the five most-cited articles in the study's database are provided.

Table 3. Top five articles with global citations.

Rank	Article's Title	Citations	Journal	Country *	Desalination Technique *	Microbial Species Used	Salt Removal Efficiency
1	A New Method for Water Desalination Using Microbial Desalination Cells [89]	609	*Environ. Sci. Technol.*	China and U.S.A.	MFC and MDC	Mixed bacterial culture	90% (Single desalination cycle)
2	Microbial desalination cells for energy production and desalination [81]	202	*Desalination*	U.S.A. and Canada	MDC	*Geobacter sulfurreducens* and *Pelobacter propionicus*	>95% (large amount of wastewater)
3	Microbial desalination cells for improved performance in wastewater treatment, electricity production, and desalination [87]	187	*Bioresour. Technol.*	U.S.A.	MDC	*Proteobacteria*, *Actinobacteria*, *Chlamydiae* and *Firmicutes*	66%
4	Stacked microbial desalination cells to enhance water desalination efficiency [88]	178	*Environ. Sci. Technol.*	China	SMDCs	*Escherichia coli*	99.4%, 85.6%, and 72.1%
5	Sustainable desalination using a microbial capacitive desalination cell [86]	112	*Energy Environ. Sci.*	U.S.A.	MCDC	Anaerobic consortium	88%

* Environ. Sci. Technol.: Environmental Science & Technology, Bioresour. Technol.: Bioresource Technology, Energy Environ. Sci.: Energy & Environmental Science, U.S.A.: United States of America, MFC: Microbial Fuel Cell, MDC: Microbial Desalination Cell, SMDCs: Stacked Microbial Desalination Cells, and MCDC: Microbial Capacitive Desalination Cell.

All the ranked articles discussed aspects of MDCs. It is evident that the research trend in biodesalination focuses on advancing the process technology and efficiency. The discussed aspects of the process were its energy production, efficiency, and sustainability.

Studies revealed that the electric potential gradient that is generated by MDC's exoelectrogenic bacteria (IEMs) is used for desalination via a succession of ion-exchange membranes [81]. It was mentioned by the researchers that the maximum current density ever recorded in an MDC was 8.4 A/m^2. Three experiments recorded salt removal efficiencies higher than 90%, two of which used a bacterial consortium. The highest efficiency recorded among the articles was more than 95% when large amounts of wastewater were used as nutrient mediums [81]. Wastewater nutrients have been proven to give microorganisms high tolerance abilities because of their hypersaline and toxic solutions. Findings of studies revealed that passive algal biocathodes outperform air cathodes, remove more COD, and employ treated wastewater to create high-value biomass for bioproducts [19]. These data show that passive mechanisms could benefit MDCs' sustainability.

Articles discussing applications of micro-organisms in the neutral/zero energy demand biodesalination process were also analyzed for citations. Table 4 represents the five most-cited articles in the study's database discussing the neutral energy demand process.

The article with the second rank in Table 4 provided the base for energy neutral biodesalination. The article outlined the availability of tools and methods for using cyanobacteria in water treatment. It covered various aspects of the process, including but not limited to strain selection, environmental factors, ion transport, and process design [79]. The results of the article mainly highlighted cyanobacteria's attributes of fast growth, tolerance to various salt concentrations, and potential for genetic manipulation.

The most-referenced article in Table 4 demonstrated the potential of merging halophytic technology with the utilization of algae for biofuel. According to the findings, with successful optimization, this procedure could be sustainable. The process will guarantee a low-cost water supply and lucrative biofuel as a byproduct that supplies electricity for the desalination process [52]. It was also described in the paper how this method may be put to use in a variety of applications, such as desalination of low-salinity brackish water or as a pretreatment for saltwater before reverse osmosis, depending on the initial salt concentration [52].

Table 4. Top five articles with global citations with the keyword 'Biodesalination'.

Rank	Article's Title	Citations	Journal *	Country *	Microbial Species Used *	Salt Removal Efficiency
1	Bio-desalination of brackish and seawater using halophytic algae [52]	33	*Desalination*	U.S.A. and U.A.E.	*Scenedesmus* sp. *and C. vulgaris*	30%
2	Biodesalination: A case study for applications of photosynthetic bacteria in water treatment [79]	30	*Plant Physiol.*	U.K.	Bacterial consortium	-
3	Biodesalination: an emerging technology for targeted removal of Na^+ and Cl^- from seawater by cyanobacteria [6]	23	*Desalin. Water Treat.*	U.K.	Bacterial consortium	-
4	Interactive effect of temperature, pH and light intensity on biodesalination of seawater by *Synechococcus* sp. PCC 7002 and on the cyanobacteria growth [62]	7	*J. Advance Res. Fluid Mechanics Therm. Sciences*	Malaysia	*Synechococcus* sp.	>50%
5	Unprecedented biodesalination rates–Shortcomings of electrical conductivity measurements in determining salt removal by algae and cyanobacteria [22]	5	*J. Environ. Manage.*	U.A.E. and U.S.A.	*P. keutzingianum*	40%

* Plant Physiol.: Plant Physiology, Desalin. Water Treat.: Desalination and Water Treatment, J. Advance Res. Fluid Mechanics Therm. Sciences: Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, J. Environ. Manage.: Journal of Environmental Management, U.S.A.: United States of America, U.A.E.: United Arab Emirates, U.K.: United Kingdom, *Scenedesmus* sp.: Scenedesmus species, *C. vulgaris*: Chlorella vulgaris, *Synechococcus* sp.: Synechococcus species, and *P. keutzingianum*: Phormidium keutzingianum.

Another measure analyzed was the NCP, which gives an estimate of the proportion of publications that have a high contribution to knowledge. An average of five citations defines a paper as a good source, and this value was used as a threshold. From the Scopus database of this study, 28 research articles were excluded from a total of 80, where their recorded citations were less than five. Fifteen research articles of the excluded recorded zero citations. The PCP was calculated as shown in Equation (4). The PCP value shows that 65% of the articles in the database were cited.

$$\mathrm{PCP} = \frac{\mathrm{NCP}}{\mathrm{TP}} = \frac{52}{80} = 0.65 \quad (4)$$

Furthermore, the co-citation measure was analyzed, where the measure represents the occurrences of publications cited together to identify similarities in the field of research. VOSviewer was used to map the co-cited articles with the 'co-citation' type of analysis and the 'cited references' as the unit of analysis. The threshold for a publication included in this analysis was set to have at least five citations. Of the 3856 cited references in the database, 19 references met the threshold. Figure 5 shows the network of references and their co-citation links.

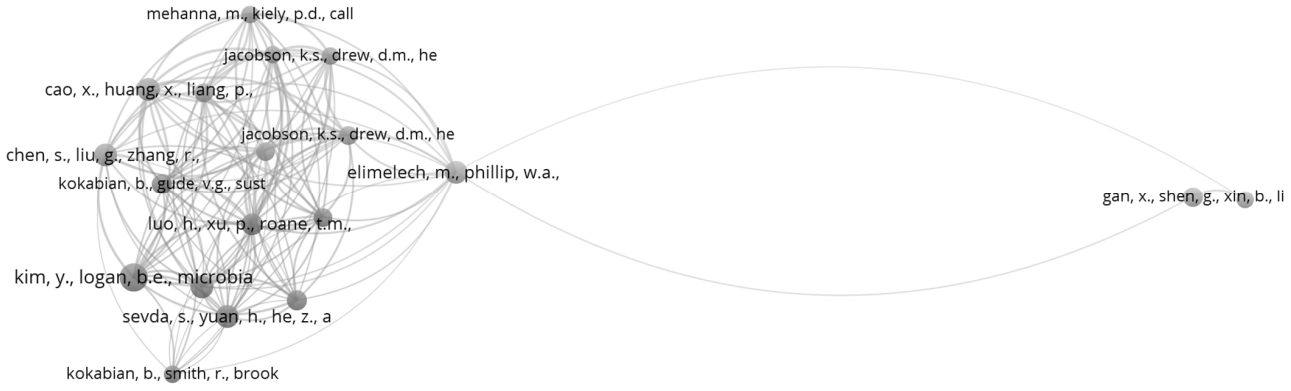

Figure 5. Co-citation network visualization on biodesalination research.

The article with a strong correlation to the other references discussed how desalination is a technical solution to global water shortages, how to reduce the process's energy consumption, and the role that innovative materials and technologies can play in improving its efficiency [97]. It also addressed concerns about the environmental impacts of seawater desalination plants on a large scale. With its detailed discussions about the factors above, it is no surprise that it has been co-cited the most. The five most co-cited articles are illustrated below in Table 5.

Table 5. Top five articles with co-citations.

Rank	Article's Title	Co-Citations	Total Link Strength	Year of Publication	Journal *	H-Index
1	Concurrent desalination and hydrogen generation using microbial electrolysis and desalination cells [98]	5	86	2010	*Environ. Sci. Technol.*	425
2	Microbial desalination cell technology: A review and a case study [99]	6	86	2014	*Desalination*	203
3	Microbial desalination cells for improved performance in wastewater treatment, electricity production, and desalination [87]	8	83	2012	*Bioresour. Technol.*	317
4	A new method for water desalination using microbial desalination cells [89]	9	80	2009	*Environ. Sci. Technol.*	425
5	Integrated salinity reduction and water recovery in an osmotic microbial desalination cell [100]	6	78	2012	*RSC Advances*	167

* Environ. Sci. Technol.: Environmental Science & Technology, Bioresour. Technol.: Bioresource Technology.

All articles with high co-citations (Table 5) relied on MDCs for desalination. This is consistent with the finding from Table 3 suggesting MDCs to be the most investigated technique. These articles also investigated integrating MDCs with other processes, which is another reason for leading the high co-citation count. The top-ranked article in Table 5 discusses a bioelectrochemical system called microbial electrolysis and desalination cell (MEDC), which has been designed to desalinate salt water, generate hydrogen gas, and treat wastewater all at once [98]. The technology improved current density by almost 60%, driving the system's salt removal efficiency up to 98.8% [98]. In addition, the article ranked fourth in Table 5 is the article that introduced MDCs in the field of biodesalination.

To shed more light on the research groups that are active in this line of research, active authors in the field producing the highest publications in the field were identified. A total of 276 authors, representing the NCA, were ranked. VOSviewer also analyzed the number of documents for each author in the database with their citations and total link strength. The ranking was performed using a normalized publications score, defined as the total number of publications in the database of the study. The number of publications threshold was set as 1. Aly Hassan A. from the United Arab Emirates University and Gude V.G. from Mississippi State University led the ranking with five documents each. The top five authors with the most documents are listed in Table 6.

Table 6. Top five authors according to the number of published articles.

Rank	Author	Documents	Affiliations	Country
1	Aly Hassan A.	5	United Arab Emirates University	U.A.E.
2	Gude V.G.	5	Mississippi State University	U.S.A.
3	Jafary T.	4	National University of Science & Technology	Oman
4	Titah H.S.	4	Institut Teknologi Sepuluh Nopember	Indonesia
5	Kokabian B.	4	Mississippi State University	U.S.A.

Using the bibliographic data in the research database, VOSviewer was further used to map the country profile using the 'co-authorship' type of analysis with 'authors' as the unit of analysis. The study was performed with a threshold of one publication for each country. Twenty-four countries were included in the database, of which three were excluded because they recorded zero co-authorships. This analysis identifies the strength of collaborations among authors and countries in the database. Co-authorship occurrences are represented by the size of the circle plotted, where a larger circle indicates more countries' co-authorships. The strength of the links is characterized by the boldness of the lines connecting the circles. A total of 21 countries were listed as visualization items.

China ranked at the top in the 'total link strength', proving the country to be involved with various collaborations, followed by Spain and the U.S.A. The total link strength here represents the number of publications two countries have co-authored. The values for the measure were 13, 9, and 8, respectively. Hungary, Indonesia, and Oman were the countries excluded from Figure 6. This section also describes the active countries contributing to the biodesalination studies. It completes the objective of the second research question (RQ:2). Analyzing Figure 6, it is revealed that most countries that are focusing on biodesalination techniques have large coastal areas. Therefore, these countries are focusing on less energy-demanding desalination techniques to meet daily water demands.

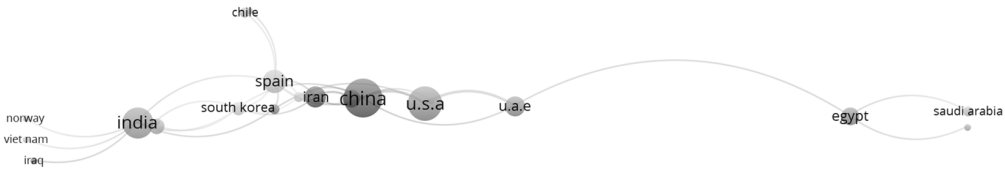

Figure 6. Co-author network visualization map of countries.

5. Discussion of Results

From the bibliometric conducted in this study, certain observations were made regarding trends in the field of biodesalination and the main contributors to this field around the world. The results consistently showed that the microbial desalination technique was the most investigated. MDCs proved to be highly efficient by reducing salinity by 45–65%. Moreover, the salt removal efficiencies can be enhanced by modifications in the selection of strains and the nature of strain. According to studies, MDCs improved COD removal by 52% and enhanced coulombic efficiency by 131% [87]. In addition, the research trend analysis revealed that six strains of cyanobacteria and ten strains of algae were investigated and discussed by the articles in the database (n = 80).

When combined with content analysis, further observations on the effectiveness of different strains of micro-organisms in desalination were noted. Few articles have shown salt reduction efficiency up to 40–45% by using *Phormidium keutzingianum* strain [7,13,14,101]. Biodesalination was performed using *C. vulgaris* and *Scenedesmus* sp. strain cultivated in brackish water and around 25–30% salt reduction was observed, respectively [52]. Some recent trends also determined the production of lipids, fatty acids, and biodiesel using species such as *Chlamydomonas reinhardtii*, *Chlorella sorokiniana*, and *Desmodesmus asymmetricus* in high saline wastewater [102–105]. From this trend, the salt stress conditions were further analyzed to investigate changes in the byproducts from microbial species at different salinity levels.

In the bibliometric analysis, China ranked first, producing the majority of publications in the database. The articles published between 2021–2022 from China are summarized in terms of their highlights in Table 7.

China's interest in sustainable desalination practices could be attributed to its uneven distribution of water resources. The country, which contains approximately 20% of the world's population, holds only 7% of the world's freshwater [106]. More than 80% of China's water supply comes from surface water, and only 60% can be made safe for drinking [8,34]. By the end of 2019, China had a desalination capacity of 1,573,760 m^3/d from 115 seawater desalination plants [107], the majority of which was used to serve the petrochemical, steel, fossil, fuel, and nuclear industries [108]. Such policies are believed to put more stress on the country's freshwater resources. On the other hand, the U.S.A. and India are not facing as critical water scarcity problems as China. Still, their interest in the field is in aims of finding alternative water resources, particularly for coastal regions.

Table 7. Highlights of China's publications between 2021–2022 in biodesalination.

Article's Title	Highlights *
Biodesalination performance of *Phormidium keutzingianum* concentrated using two methods (immobilization and centrifugation) [13]	- Chloride ion measurements suggest that *P. keutzingianum* accumulates salt through biosorption and bioaccumulation. - *P. keutzingianum* cell activity continued under harsh experimental conditions.
Simultaneous desalination and ammonia recovery using microbial electrolysis desalination and chemical-production cell: A feasibility study of alkaline soil washing wastewater [26]	- Bioenergy provided 58% of the wastewater treatment process's energy. - The MEDCC desalinizes efficiently. - High current density from decreased membrane fouling, enhanced wastewater conductivity, and EAB improved desalination.
Algae-assisted microbial desalination cell: Analysis of cathode performance and desalination efficiency assessment [27]	- Microalgae produce dissolved oxygen that may promote ion migration in an MDC system. - The microalgal-assisted biocathode can self-sustain a steady oxygen concentration, regenerate from loss cost-effectively, and sustainably maintain system performance in natural environments.
Life cycle assessment for algae-based desalination system [30]	- Algae-based desalination systems consume land and deplete scarce minerals. - The operating phase causes half to two-thirds of the environmental impact.
Life-cycle cost analysis of a hybrid algae-based biological desalination—low pressure reverse osmosis system [34]	- A hybrid desalination system is more cost-effective than an algae-based system since it requires less land. - Reusing algal biomass may make an algae-based desalination system economically viable. Algal biomass may be used to create biodiesel, food additives, and biogas.

* *P. keutzingianum*: Phormidium keutzingianum, MEDCC: Microbial Electrolysis Desalination and Chemical-production Cell, EAB: Electrochemically Active Bacteria, MDC: Microbial Desalination Cell.

6. Recent Developments in Biodesalination

This section summarizes advancements in biodesalination in 2021 and 2022, highlighting research opportunities in the field. The advancements are summarized in Table 8 with identified research gaps. The table groups the advancements into four themes: the implemented technology; modifications to nutrient media; investigated strain of micro-organism; and integration with a renewable source of energy.

The internal and external resistance was proven to lower the MDC salinity removal efficiency [109]. MDC desalination uses both electrical and concentration gradients [44].

Anions and cations flow toward the anode and cathode chambers owing to the electrical gradient, whereas the concentration gradient accounts for the difference in salt concentration between the center and side chambers [23]. Comparing MFC and MDC systems for power generation, it was found that as the systems' external resistance decreased, their current generation increased, enhancing salinity removal efficiency [110].

A significant factor determining biodesalination's potential is strain selection, where different strains have distinctive salinity tolerance, ion uptake, and salt removal capacities [7,8,52]. Strain selection is time-consuming and challenging due to the large number of species available. According to a conservative estimate, there are around 72,500 algae species in the world today, of which only 32,260 have been described [7]. During the last two years, the three strains studied for biodesalination with publications were *P. keutzingianum* [13,14,22,101], *C. vulgaris* [41,49,52,111], and *Coelastrum morus* [112].

Table 8. Recent advancements and research gaps.

	Research Advancement *	Research Gaps
Technology	- By decreasing external resistance, the MDC system could generate higher current for biodesalination [23]. - MDCC utilizes wastewater as fuel to generate electricity [20].	- Investigating the impact of externals and internal resistance reduction on biodesalination's efficiency. - Investigating the causes of the decline in salt removal efficiency when more treatment days are considered.
Nutrient Media	- *C. vulgaris* microalgae were grown in BG11 modified with nitrate, calcium, and potassium instead of chloride and sodium. Growth rate and salt removal efficiency increased [36]. - *P. keutzingianum* different preparation methods may promote biodesalination [13]. - Wastewater enhanced cyanobacteria growth and salinity tolerance [18].	- Investigating effects of different ecosystems and environments on specific micro-organisms' efficiencies. - Development of nutrient media modifications standards.
Strain Selection	- *P. keutzingianum* is stress-tolerant [14]. The strain produced biomass, bioabsorbed, bioaccumulated, and biomineralized throughout a broad salinity range. - *S. arcuatusa* removal efficiency increased from 32.42 to 48.93% under high light intensity and CO_2 supply [14]. *Nannochloropsis* sp. could grow in desalination brine.	- Exploring efficiencies and tolerances of different strains of alga (72,500 algae species in the world today, of which only 32,260 have been studied).
Renewable Energy	- Innovations in solar membrane distillation based, portable REDES systems [19]. - Bioenergy provided 58% of the wastewater treatment process's energy [26].	- Upscaling experiments with integrated renewable energy sources. - Reducing the time required for power generation before biodesalination

* *P. keutzingianum*: Phormidium keutzingianum, *S. arcuatusa*: Scenedesmus arcuatusa, *C. vulgaris*: Chlorella vulgaris, *S. arcuatus*: Sollasites arcuatus, MDC: Microbial Desalination Cell, MDCC: Microbial desalination and chemical recovery cell, REDES: Renewable-Energy-driven Desalination.

P. keutzingianum is a halotolerant terrestrial cyanobacterium with a filamentous structure [13]. Zafar et al. [14] and Shaikhoun et al. [13] experimented with the strain *P. keutzingianum* at different salinity levels to test its salt tolerance. The salt solutions, ranging from brackish to hypersaline, had NaCl concentrations of 10, 30, 50, and 70 g/L. The strain achieved a removal efficiency of 40% in a total of 80 treatment days in a salinity of 10 g/L [22]. For the three other solutions, the strain achieved a removal efficiency of 46%, 44%, and 29% in a total of 68 treatment days, respectively [14]. The experiments were made using the suspension treatment method. For the growth of the strain, the

nutrient media BG-11 + 1% NaCl medium recipe and light intensity of 2885 lux were used. Estimates of biomass growth indicated that the examined strain is adaptive to all salinity levels tested. This result is of critical importance, proving that strains of cyanobacteria can tolerate high salinity levels and achieve outstanding salinity removal within an appropriate time frame, especially keeping in mind the cost of the process, its energy consumption, and environmental effects. It was observed in the experiment that the salinity removal efficiency decreased with the increasing salinity in the solutions, but still, the efficiencies were acceptable.

The freshwater microalga *C. vulgaris* was the first photosynthetic micro-organism isolated and cultivated in pure culture [113]. This strain was experimented with for salt removal efficiency in different salt-concentrated solutions of 1000 to 4000 ppm [36]. *C. vulgaris* achieved 80% removal efficiency in a total of 15 treatment days when using a nutrient media of a modified BG-11 and a Lux of 1700. The BG11 nutrient medium was adjusted by replacing the chloride and sodium salts with nitrate, calcium, and potassium minerals. The results of the dry weight, which indicates growth, demonstrated that the modified-BG11 nutrient medium significantly improved microalgae growth. Salinity was decreased when the growth of new cells dominated the death phase of living cells.

Coelastrum species (*Coelastrum* sp.) have lately received increased attention due to their capacity to accumulate lipids and pigments and their use in wastewater treatment [112]. Findings from a study indicated that minor variations in nutrient media's nitrate and phosphate concentrations have led to different algal growth rates [112]. Increased nutrient content has led to higher salt tolerance capacity. It was indicated that a combined concentration of high nitrate and phosphate, above 100 mg/L, is not the best environment for green alga growth [56]. The *Coelastrum* sp. examined was classified as a halotolerant, exhibiting extraordinary growth up to 1000 mg/L NaCl [112]. Furthermore, it was observed from the literature that the higher the growth of the microbial species, the higher salt removal efficiencies can be achieved [56,59].

Regarding energy consumption, MDCs, when fully developed, might provide a reliable and practical means of extracting freshwater with exceptionally low energy usage. Furthermore, unlike traditional renewable energy, MDCs function constantly, reducing the need to oversize the desalination unit for a specific freshwater demand. Studies have shown that using solar photovoltaic energy as an external energy source could considerably contribute to developing small-capacity brackish water desalination systems. An external voltage was applied in a study [19], which had outstanding results for enhancing the salt removal rate. Furthermore, the experiment demonstrated that the improved salt removal might be high enough to create fresh water from seawater without needing a separate desalination process to treat the MDC product [19]. This innovation, like its predecessors, creates a new perspective in biodesalination, where scientists focus on making what is now utilized more efficiently. Currently, the prospects of MDCs are primarily based on developing upscaling capacity, enhancing productivity, and lowering product prices through the generation of valuable byproducts.

7. Conclusions

This study aimed to identify research trends, major contributors, and highlight recent advancements in biodesalination. The results of the bibliometric analysis revealed that research in the field of biodesalination is booming with increasing publications and citation. It was also perceived from the analysis that co-authorship between different countries and organizations is not common and collaboration could be improved in the field. This was supported by the co-authorship analysis for different countries, which highlighted only 21 countries with research ties, with China leading the ranking in global collaboration ties.

Recent advances substantiate strain selection as the most challenging task. There is a vast variety of species available, and their choice affects the biodesalination process significantly. Modifying microbial species' nutrient and solar energy needs could result in different growth rates and strain characteristics, such as increased salinity tolerance. In

addition, it was discovered that substituting chloride and sodium salts with nitrate and potassium minerals improves growth rates and salt removal efficiencies.

This research might help researchers understand the present body of knowledge in the field of biodesalination and guide future research agendas. The following future research opportunities were revealed from the analysis:

1. Investigating the impact of novel modifications to nutrient media on the effectiveness of biodesalination by different species.
2. Investigating the impacts of varying environmental conditions and salinity on cell growth and viability.
3. More importantly, more investigation on the upscaling of biodesalination to deal with real-world water volumes is a critical endeavor. This will help form a clearer perspective towards the salt removal efficiencies of different technologies (MDCs, etc.) and define what could be done for improvement.

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