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Knowledge Mapping of High-Rate Algal Ponds Research

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Abstract: High-rate algal ponds (HRAPs) are a highly promoted wastewater treatment system that uses sunlight as an energy source to provide the oxygen needed in the system through photosynthesis and has a high nutrient and organic matter removal capacity. In addition, the microalgae in the system can use wastewater as a growth substrate to produce valuable bioproducts, biomaterials, and bioenergy, so it is receiving more and more attention. This review uses bibliometric analysis to explore current research hotspots and future research trends in this emerging technology. By analyzing research papers related to HRAPs published in the Web of Science (WOS) from 1987 to 2021 based on the co-occurrence and clustering of keywords, it shows that the research hotspots of HRAPs are mainly focused on wastewater treatment, nutrient removal, microalgal biomass, biofuel, and biogas upgrading. In the future, in-depth research will continue to be added on the contribution of HRAPs to environmental sustainability, including *E. coli* removal, biogas upgrading and oxygen removal, treatment of aquaculture wastewater, purple phototrophic bacteria, aqueous biorefineries, and biorefineries. The results assist scholars in systematically understanding the current research status, research frontiers, and future trends of HRAPs from a macro perspective.

Keywords: HRAPs; knowledge mapping; bibliometric analysis; wastewater treatment

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1. Introduction

High-rate algal ponds (HRAPs) were proposed and developed by Oswald, Gotaas, and colleagues at the University of California in the 1950s [1]. The HRAPs are a modified stabilizing pond that intensifies algae proliferation to generate an environment favorable for microbial growth and reproduction, resulting in an intense algal-bacterial symbiosis [2]. HRAPs are designed as an open-channel, race-track-style pond. Wastewater is gently circulated around the HRAP via a single paddle wheel at velocities between 0.15 and 0.3 m s^{-1}. The paddle wheel also creates turbulent eddies that provide a degree of vertical mixing in the water column. The shallow water depth, typically between 0.2 and 0.7 m, coupled with vertical mixing allows microalgae to proliferate to high biomass concentrations [3]. Compared to traditional biological treatment technologies, this technology has the advantages of low investment and low running costs; it does not require large areas of land to be used, and the process is simple. Compared to conventional ponds, HRAPs offer improved nutrient removal and natural disinfection, with the added benefit of resource recovery, in the form of algal biomass for beneficial reuse as fertilizer, feed, or biofuel. Additionally, HRAPs have a substantially greater DO content than traditional stable ponds. The main factors affecting DO in HRAPs are the alternation of photosynthesis and respiration of algae, the respiration of bacteria, and atmospheric dissolution [2,4–7]. According to synergy in physiological activities between the two types of organisms, algae and bacteria, the removal of contaminants by HRAPs is primarily performed by their combined activity. Algae use sunlight as their energy source, CO_2 as their carbon source, and ammonia as their nitrogen source to synthesize new algal cells through photosynthesis of chlorophyll in algal cells and release large amounts of O_2 for bacteria to circulate and degrade organic matter, achieving low carbon and low energy consumption. Aerobic bacteria oxidize and degrade the organic matter in wastewater, converting it into small molecules of inorganic matter while producing CO_2 [8–10]. Currently, HRAPs are developing in household wastewater treatment, livestock, and aquaculture fields in China, the United States, Germany, France, Singapore, Mexico, Brazil, and other countries [11]. Studies have shown that when HRAPs are used to treat rural domestic wastewater in China, the discharge of TN and TP is controlled to below 5 mg/L and 1 mg/L, respectively, which meet the discharge standard of GB 189182-2002 Class 1 B [12]. To accomplish resource recovery, the wastewater treatment paradigm must be changed [7]. HRAPs systems can be used to construct a form of sustainable wastewater treatment [13], thus becoming a prevalent wastewater treatment technology with great potential for development.

Traditional review is a qualitative summary, inductive ideas, and analysis of the theme [14]. To comprehend the distributed architecture and collaboration of scientific effort and discovery, the bibliometric analysis was performed using mathematical and statistical approaches to analyze the published literature from a macro viewpoint [13]. Bibliometrics is frequently acknowledged as one of the best techniques for illuminating the organization and relationships of the body of information accumulated in a certain field or discipline, as well as for evaluating and forecasting research trends on a specific subject [15–19]. Additionally, the subjective bias of the literature review is reduced by relying on computer-generated objective evaluations [20]. The statistical results, which typically comprise words and the literature, can evaluate year-to-year variations in the number of pertinent studies, the performance of critical national outputs and international collaborations, identify hot issues in the area, and reveal future research directions. Numerous recent bibliometric studies have been conducted in various subjects, including agriculture, the environment, materials, medicine, and other disciplines. In the existing literature, standard bibliometric software tools include VOSviewer [21], CiteSpace [22], SciMAT [23], CiteNetExplorer [24], Bibliometrix [25], HistCite [26], et al. We conduct a thorough bibliometric analysis to deepen our understanding of HRAPs and pinpoint the main themes and thematic gaps in research.

This study utilized bibliometrics for the first time to analyze HRAPs' research applications for wastewater treatment internationally to obtain more insight into the development, general status, and trend of HRAPs' research. The following are the specific research contents: Research dynamics of HRAPs include the number of publications and trends in the field, the principal research nations and their geographic distribution, the central institutions and authors, the top academic journals in the area, the number of critical papers with network relationship analysis, and keyword co-occurrence based on co-authorship. The evaluation and analysis of the figures, patterns, research groups, and frequency of references in the detected documents led to the creation of social network maps. Furthermore, a cluster analysis of terms was used to determine the research hotspots and future directions of HRAPs. A thorough bibliometric study offers references and suggestions for future researchers while also advancing our awareness of the state of scientific advancements in this field.

2. Methods

2.1. Data Collection

A large selection of the literature in engineering, science, management, social sciences, and the humanities is available in the Web of Science (WoS) database, which includes the majority of pertinent periodicals. The data for this research paper were collected from the WoS website in June 2021 with the following search strategy: Topics = "high rate algal pond *"; Timespan = "All year"; The database used in this study includes all types of indexes, namely Science Citation Index Expanded (SCI-EXPANDED), Emerging Sources Citation Index (ESCI), Social Sciences Citation Index (SSCI), Book Citation Index-

Science, Book Citation Index-Social Sciences and Humanities (BKCI-SSH), Conference Proceedings Citation Index-Science (CPCI-S), and Arts and Humanities Citation Index (A & HCI). In addition, since English is the language used in most scholarly research, this study exclusively shortlisted English-language papers. Only research publications were considered, with all other documents such as review papers and proceedings, meeting abstracts, early access, editorial content, data papers, and letters being eliminated. In the end, 293 articles were found and exported for analysis in this study after duplicate documents were deleted.

2.2. Data Analysis

HRAPs were further studied and analyzed using VOSviewer and CiteSpace. The useful software VOSviewer was developed in 2007 by researchers at Leiden University in the Netherlands for the construction and viewing of bibliometric networks. VOS stands for visualization of similarity. In this study, it was utilized to identify the collaborative and co-occurrence networks of the contributors. It helps to reflect the researchers' networks of collaboration and co-authorship. Using the symbiosis matrix as a base, VOSviewer creates a map. The map is first made by creating a similarity matrix based on the symbiosis matrix. Next, use the VOS mapping approach to generate the matrix [21,25,27–29]. The map is then panned, rotated, and reflected, and things with high relevance are grouped to create clusters. To help distinguish various clusters, different colors are randomly allocated to each cluster [30]. CiteSpace is a Java-based information-based visual analysis program created by Chaomei Chen and widely used in various subjects [22,25,27,28,31]. Based on a sizable amount of bibliometric data, it can be utilized to study co-citation networks [32]. Numerous academics have utilized CiteSpace in the past to review the literature across many disciplines, including those about sustainable development. Researchers may benefit from a complete, visual tool that concisely describes the research hotspots and potential future directions of a specific topic by combining bibliometrics with CiteSpace [33]. The most pertinent keywords were manually chosen to exclude redundant and irrelevant terms from the analysis. For instance, "algae" and "microalgae," "biogas" and "biogas upgrading," and "biomass" and "microalgal biomass" were combined.

3. Results and Discussion

3.1. Trend Analysis of Article Issuance

The trends in the number of HRAPs' publications and citations from 1987 to 2021 are shown in Figure 1. The low number of publications from 1987 to 2012, with an annual average of fewer than 10, indicates that HRAPs' technology was at an early research stage. The exponential increase in the number of publications from 2013 to 2017, from 10 in 2013 to 39 in 2017, indicates that HRAPs' technology gradually attracted the attention of scholars and increased research during that period, and the number of research results increased. However, the number of articles issued from 2018 to 2021 decreased significantly in the annual number of articles issued, from 39 in 2017 to 17 in 2019, with a decrease of 22 articles. The average annual number of publications for 2019–2021 is 22.

Moreover, the number of cited articles about HRAPs from 1987 to 2021 is consistent with the number of publications in Figure 1, showing that the overall number of cited articles from 1987 to 2012 is low and less volatile. The number of articles published from 1995 to 2007 has slightly increased compared to before 1994, but the overall fluctuation is also not significant, basically maintaining around 30 articles. In addition, the number of cited articles increased exponentially from 2008 to 2020, from 62 to 1690. It is inferred that this period was a period of rapid growth in HRAPs' research.

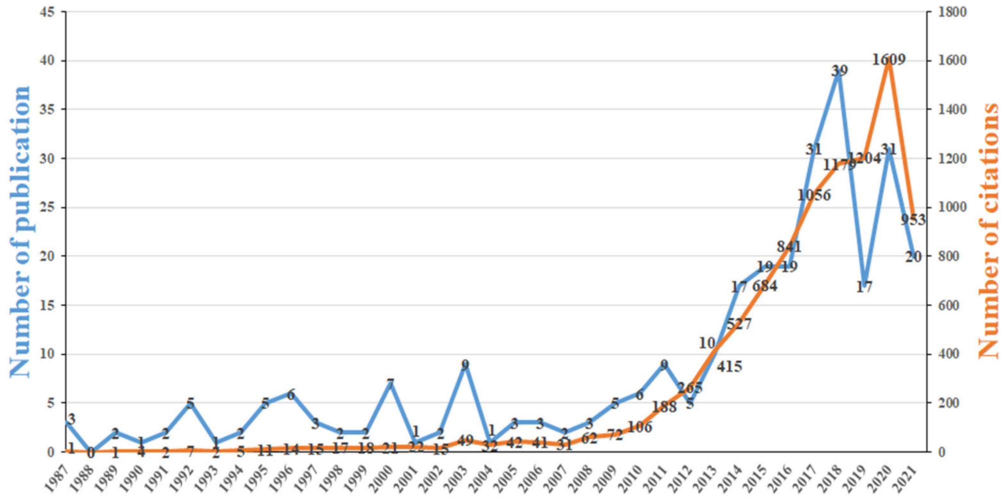


Figure 1. Annual trends in the number of publications and citations.

3.2. Country Distribution and Cooperation Analysis

Figure 2a shows the global distribution of HRAPs' research article publication density. It is clear that the majority of relevant studies are centered in Europe, followed by Oceania. The region with the most publications was Spain (n = 74, 25.26%), followed by New Zealand (n = 59, 20.14%), Australia (n = 33, 11.26%) and Brazil (n = 26, 8.87%). Figure 2b depicts the cooperation between countries/regions. According to the analysis of the figure, the cooperation between countries/regions is generally low in intensity in this area of research, except for the relatively close cooperation between the top four publishing countries mentioned above. The frequency of cooperation between countries/regions shows that Spain and Brazil are the countries with the closest cooperation (Table 1). The main reason for the highest number of publications in Spain and the close cooperation with other countries may be related to the wastewater microalgae cultivation project launched in Spain by the third-largest water treatment company in the world, Aqualia, together with five other European companies. The project was strongly funded by the EU Innovation and R&D Fund and started in May 2011 for five years. It is the primary cause of the large increase in publications seen in Figure 1 after 2012.

Table 1. Cooperation among countries/regions.

From	To	Frequency
Spain	Brazil	6
Spain	Mexico	5
Spain	New Zealand	5
Belgium	Morocco	4
Spain	Australia	4
Spain	France	4
Spain	Honduras	4
Australia	United Kingdom	3
Belgium	Tunisia	3
Italy	Tunisia	3

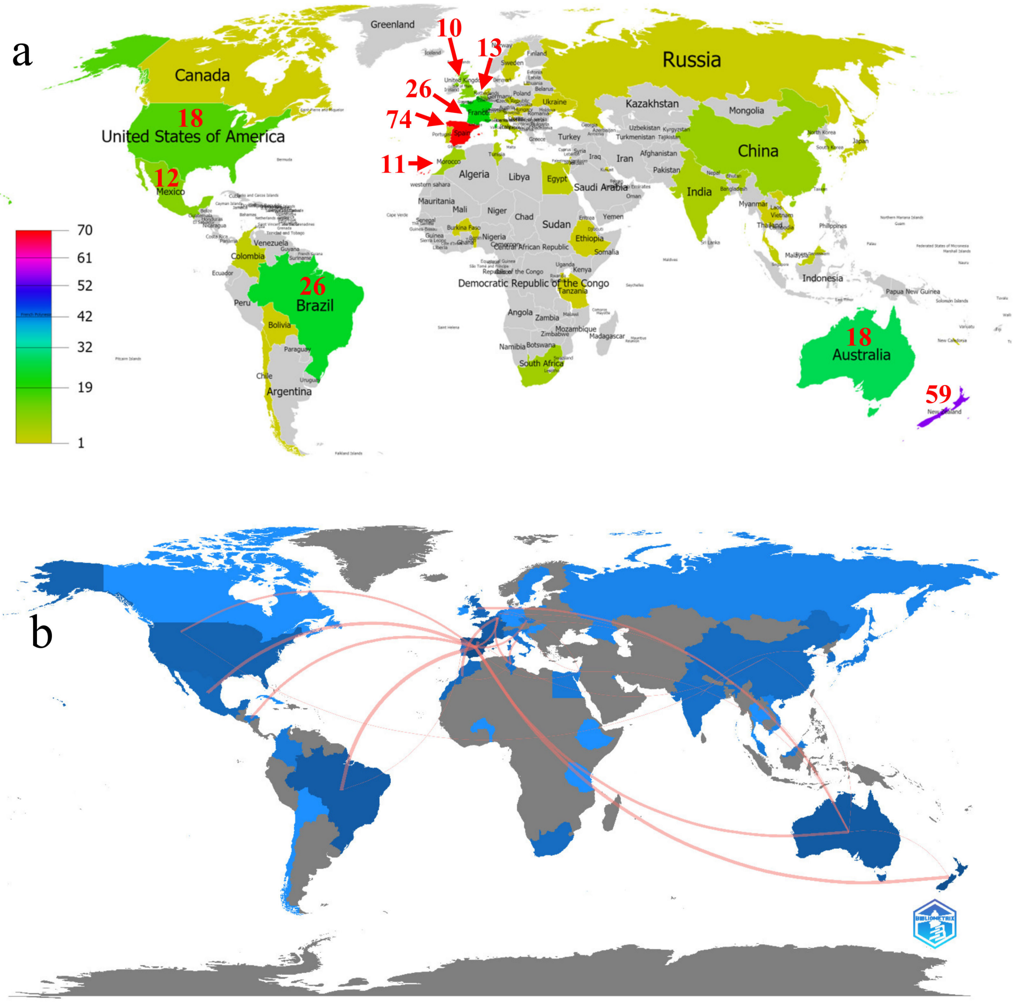
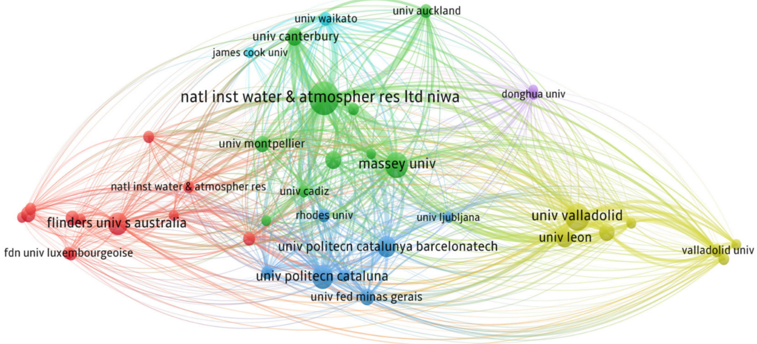


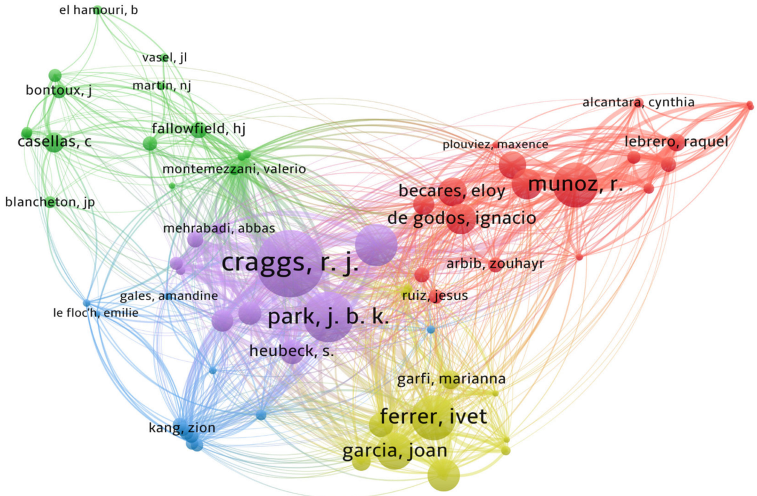
Figure 2. (**a**) global distribution of article publication density; (**b**) country collaboration map.

3.3. Institutional and Author Cooperation Analysis

The most successful and influential institutions can be found through an analysis of organizational collaboration [34]. The knowledge domain network of institutional cooperation is graphically shown in Figure 3a. Each node in the network represents a different institution, and the thickness of the connecting lines shows the level of cooperation between institutions. NIWA (National Institute of Water and Atmospheric Research) is the most significant node. It is closely related to other clusters such as Univ Valladolid (University of Valladolid), Flinders Univs Australia (Flinders University), and Univ Politecn Cataluna (Polytechnic University of Catalonia), indicating frequent cooperation with foreign institutions. The green cluster mainly includes NIWA, Massey Univ (Massey University), Univ Canterbury (University of Canterbury), and Univ Fed Vicosa (Federal University of Vicosa), which also shows that the research institutions of New Zealand have close cooperation with domestic universities and other institutions abroad. As shown in Table 2, four out of the top ten institutions are from Spain, three from New Zealand, and the remaining three are from each of Australia, Brazil, and Mexico. With 36 articles, NIWA has the most, demonstrating a greater academic influence.



(**a**)



(**b**)

Figure 3. (**a**) visualization of institutional cooperation network; (**b**) visualization of author cooperation network.

Table 2. Top 10 organizations contributing to research on HRAPs.

Organization	Region	Number of Publications
Natl Inst Water Atmospher Res Ltd NIWA	New Zealand	36
Univ Valladolid	Spain	21
Massey Univ	New Zealand	18
Univ Politecn Cataluna	Spain	17
Flinders Univ S Australia	Australia	16
Univ Leon	Spain	12
Univ Politecn Catalunya Barcelonatech	Spain	12
Univ Canterbury	New Zealand	10
Univ Fed Vicosa	Brazil	9
Univ Nacl Autonoma Mexico	Mexico	9

Author collaboration is crucial to research creativity and the sharing of outcomes. The collaborative network analysis of the literature authors in the field of HRAPs' research was conducted, and the results are shown in Figure 3b. The information on the number of authors published and cited is listed in Table 3. Depicts the author collaboration network in this field of study as being organized into five clusters, with authors working closely together within each cluster. For instance, Craggs, R.J., Park, J.B.K., and Sutherland, Donna L., are all members of the same cluster (purple), demonstrating their close cooperation and regular communication. As a result, they have co-authored numerous HRAPs' research articles [6,35,36]. In addition, Craggs, R.J., has solid academic collaborations with authors such as Munoz, R. (red cluster), Ferrer, Ivet, and Garcia, Joan (yellow cluster). The largest node corresponding to Craggs, R.J., indicates that it is the author with the highest number of publications and the most intensive links. As seen in the total link strength (Table 3), Craggs, R.J., has 39 publications and a link strength of 1461 and is the only author with more than 2000 citations. The three authors with more than 1000 citations were Park, J.B.K., Munoz, R., and Ferrer, Ivet, who also had a relatively high number of published articles. As a result, the top ten most influential authors in the field have published not only a large number of articles but also highly cited articles. The clusters were analyzed, and the highly productive purple cluster authors focused on the economic benefits and environmental footprint of dewatering algal/bacterial biomass into crude oil and algal biofuels. Author articles in the purple cluster have more citations than the other clusters and are not as relatively isolated as the blue and green clusters. It can mean that the aforementioned research fields have attracted more interest from researchers and are currently hotspots for research.

Table 3. Top 10 most impactful authors in HRAPs based on the number of citations.

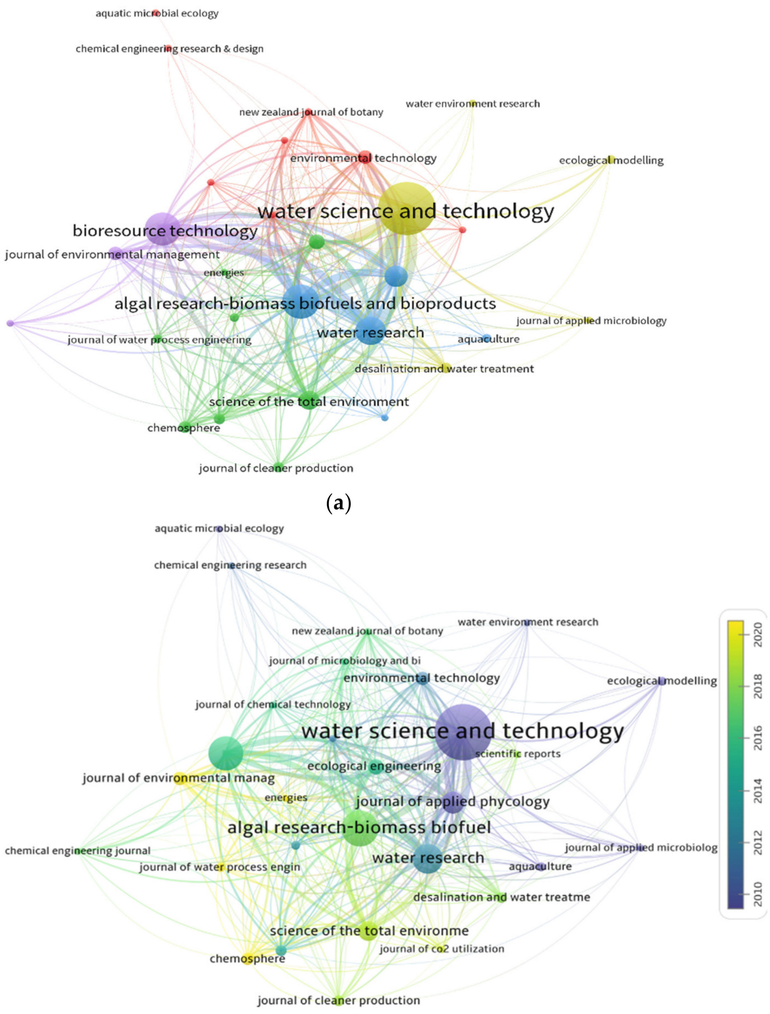
Authors	Documents	Citations	Total Link Strength	Cluster
Craggs, R.J.	39	2194	1461	5
Munoz, R.	24	1081	620	1
Ferrer, Ivet	22	1076	518	4
Park, J.B.K.	17	1331	813	5
Garcia, Joan	16	777	390	4
Fallowfield, Hj	15	193	121	2
Passos, Fabiana	12	621	266	4
Sutherland, Donna L.	11	336	466	5
Casellas, C.	11	264	82	2
Turnbull, Matthew H.	9	309	399	5

3.4. Analysis of Academic Journals and Reference Co-Citation

It is required to identify the top journals in the desired research area to comprehensively map the trends in the field [37]. The collaborative network of publications that publish papers relating to HRAPs' research is shown in Figure 4, with various node sizes denoting the total number of articles published in each journal and various node colors denoting various research clusters. The characteristics of the top ten journals in terms of divisions, the number of articles issued, and total citations for HRAPs' research publications are shown in Table 4. Figure 4a makes it clear that the nodes of the journals *Water Science and Technology*, *Algal Research, Biomass Biofuels and Bioproducts*, *Bioresource Technology*, and *Water Research* are more visible than those of other journals, indicating a higher degree of contribution to HRAPs' research. The connecting lines' thickness indicates the cross-referencing or strength of the connection to other journals. As shown in Figure 4a, *Algal Research Biomass Biofuels and Bioproducts* and *Water Research* are the two journals with the strongest link strength. The similarity of the journals' subject areas or the sum of their citation counts is used to group them into clusters. For example, *Water Science and Technology*, *Desalination and Water Treatment*, *Ecological Modelling*, *Journal of Applied Microbiology*, and *Water Environment Research* belong to the same category (yellow category). Furthermore, *Algal Research Biomass Biofuels and Bioproducts*, *Water Research*, and the *Journal of Applied Phycology* belong to the blue category. The purple category mainly includes *Bioresource Technology*, the *Journal of Environmental Management*, and the *Chemical Engineering Journal*. The strength of the link between cluster members is indicated by the size of the connection line. As shown in Table 4, the top three journals with the highest total citations in this research area were *Bioresource Technology* (1740), *Water Science and Technology* (1157), and *Water Research* (760), indicating the strong influence of these journals. The top five journals with the highest number of publications, were *Water Science and Technology* (62), *Algal Research Biomass Biofuels and Bioproducts* (31), *Bioresource Technology* (29), *Water Research* (23), and *Journal of Applied Phycology* (13). In addition, the top ten journals are mostly Q1-level (Table 4), which indicates that HRAPs' research has received significant attention from the academic community and has good prospects for development. It is also critical to understand how long each magazine takes to publish these articles because this information can reveal patterns in journal publishing. From Figure 4b, it can be seen that most of the articles, especially in *Water Science and Technology*, were published in 2010–2014, while from 2020 onwards, most of the articles are from *Chemosphere*, *Journal of Environmental Management*, and *Journal of Water Process Engineering*, which indicates that the above journals have increased their focus on this research area in recent years.

Table 4. Top 10 contributing sources.

Source	Quartile of JCR	Number of Publications	Citations	Av. Citations	Total Link Strength
Water Science and Technology	Q3	62	1157	19.28	3666
Algal Research Biomass Biofuels and Bioproducts	Q1	31	486	16.76	4791
Bioresource Technology	Q1	29	1740	64.44	3076
Water Research	Q1	23	760	36.19	4334
Journal of Applied Phycology	Q1	13	725	55.77	2624
Science of the Total Environment	Q1	12	219	19.91	1793
Ecological Engineering	Q2	7	216	30.86	1468
Journal of Environmental Management	Q1	7	20	3.33	1028
Chemosphere	Q1	6	44	8.8	704
Environmental Technology	Q3	6	54	9	955



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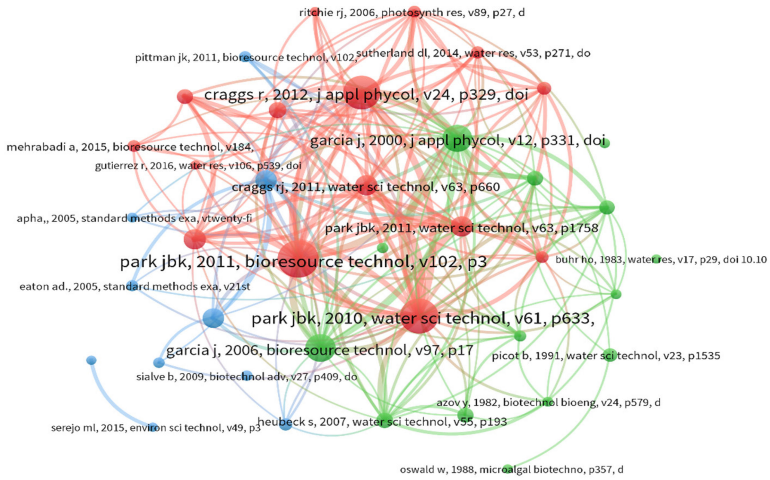

(**c**)

Figure 4. (**a**) visualization of the network of published journals; (**b**) visualization of the year of publication of journals; (**c**) visualization of the reference co-citation network.

Co-citation is the commonality with which two documents are cited together by other records [38]. By categorizing publications into distinct clusters, co-citation analysis can be used to quantify the similarity of documents and find narrative trends in the research field [39]. Figure 4c shows the co-citation network of references cited more than 14 times by HRAPs' research scholars, and the network shows a total of 39 references that meet this threshold. Different colors represent different clusters, and the node size is proportional to the frequency with which the article is cited. The total link strength indicates the total strength of a unit linked to other units, and the greater the total link strength, the closer it is to other units. The specific citation information for the top ten co-cited documents is listed in Table 5. According to Figure 4c, the 39 references were divided into three clusters based on their co-citation relationships. By analyzing the titles and abstracts of each reference in the three clusters, the main research themes of each cluster were identified. The top ten references based on co-citation are displayed in Table 5. The red cluster is the largest, with 15 references. The research focused mainly on the economic benefits and environmental footprint of algal biofuel production from HRAPs in wastewater treatment, algae recovery, and crude oil preparation. The article *Wastewater treatment high-rate algal ponds for biofuel production* by Park, J.B.K. et al. [6] is the most cited paper (57 citations) and the paper with the highest total link strength (165) in this cluster, hence, it can be regarded as the core article. With a total of 14 citations, the green cluster is the second most significant. The study mainly focused on removing pollutants and ammonia nitrogen from wastewater by HRAPs. In this cluster, the article *Long-term diurnal variations in contaminant removal in high-rate ponds treating urban wastewater* by Garcia, J. et al. [40] has the highest number of citations (42 citations) and the highest total link strength (109), so it is considered a core article in the green cluster. The blue cluster has ten references, making it the smallest cluster. Its research focuses on the long-term operation of HRAPs' bioremediation of swine farm wastewater at high loading rates and the process of algae–bacterial treatment of harmful pollutants. The core publication in the cluster with the most citations (30 citations) and the highest total link strength (86) is *Long-term operation of high-rate algal ponds for the bioremediation of piggery wastewaters at high loading rates* by Ignacio de Godos et al. [41]. According to the analysis of the literature authors in Table 5, Craggs, R.J., and Park, J.B.K., collaborated on four papers, two of which were cited more than 50 times. The paper *Wastewater treatment high-rate algal ponds for biofuel production* was the most cited paper in the field. The paper focuses on the significant economics and small environmental footprint of algal biofuels produced during HRAPs' wastewater treatment compared to other fuels [6]. The article also details key parameters limiting algal culture, production, and harvesting and discusses possible ways to increase net algal harvest in wastewater treatment. The remaining two co-authored articles have 31 citations, which shows that both authors, Craggs, R.J., and Park, J.B.K., are more representative in the field of HRAPs' research. From the overall view of the analysis of the literature authors in Table 5, three citations exceeded 50, two exceeded 40, and the remaining five were all over 30. According to the analysis of the literature sources, three of these ten papers were from Bioresource Technology, three from *Water Science and Technology*, two from *Water Research*, and two from the *Journal of Applied Phycology*.

Table 5. Top 10 references by co-citation.

Reference	Author	Source	Local Citations	Links	Total Link Strength	Cluster
Wastewater treatment high-rate algal ponds for biofuel production	J.B.K. Park, R.J. Craggs, A.N. Shilton	*Bioresource Technology*	57	38	165	1
Wastewater treatment and algal production in high-rate algal ponds with carbon dioxide addition	J.B.K. Park, R.J. Craggs	*Water Science and Technology*	53	38	159	1
Hectare-scale demonstration of high-rate algal ponds for enhanced wastewater treatment and biofuel production	Rupert Craggs, Donna Sutherland, Helena Campbell	*Journal of Applied Phycology*	51	37	129	1
Long-term diurnal variations in contaminant removal in high-rate ponds treating urban wastewater	J. García, B.F. Green, T. Lundquist, R. Mujeriego, M. Hernández-Mariné, W.J.Oswald	*Bioresource Technology*	42	36	109	2
High-rate algal pond operating strategies for urban wastewater nitrogen removal	Garcia, J, Mujeriego, R, Hernandez-Marine, M	*Journal of Applied Phycology*	41	36	128	2
Algal biofuels from wastewater treatment high-rate algal ponds	R.J. Craggs, S. Heubeck, T.J. Lundquist, J.R. Benemann	*Water Science and Technology*	31	34	95	1
Recycling algae to improve species control and harvest efficiency from a high-rate algal pond	J.B.K. Park, R.J. Craggs, A.N. Shilton	*Water Research*	31	35	89	1
Nutrient removal in wastewater treatment high-rate algal ponds with carbon dioxide addition	J.B.K. Park, R.J. Craggs	*Water Science and Technology*	31	34	104	1
Long-term operation of high-rate algal ponds for the bioremediation of piggery wastewaters at high loading rates	Ignacio de Godos, Saúl Blanco, Pedro A. García-Encina, Eloy Becares, Raúl Muñoz	*Bioresource Technology*	30	37	86	3
Algal–bacterial processes for the treatment of hazardous contaminants: A review	Raul Munoz, Benoit Guieysse	*Water Research*	30	34	62	3

3.5. Keyword Clustering Network Analysis

Research trends, present and developing themes, and more nuanced and significant research trends can all be predicted using keyword co-occurrence analysis [42]. As a result, this study uses VOSviewer software to visualize the knowledge mapping of the keyword co-occurrence network, as seen in Figure 5a. Some non-keywords are not displayed to prevent overlap, and each node represents a keyword. The frequency of each keyword is indicated by the size of the circle, its co-occurrence is symbolized by the curve connecting the circles, and the strength of the association is represented by the thickness of the curve [43]. The closer two keywords are in the network, the closer the association is, and the different colors indicate the categorical clustering of the keywords.

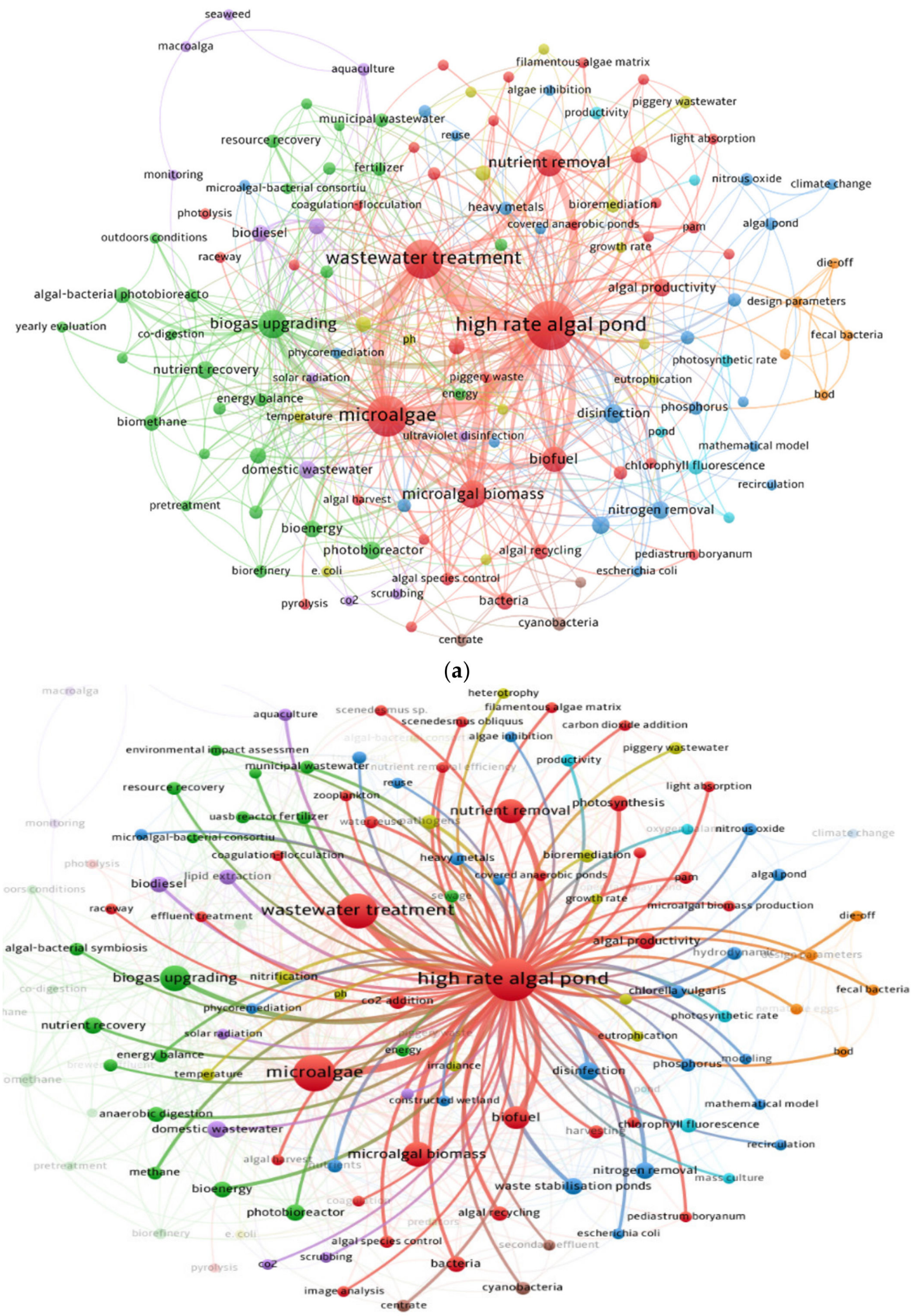

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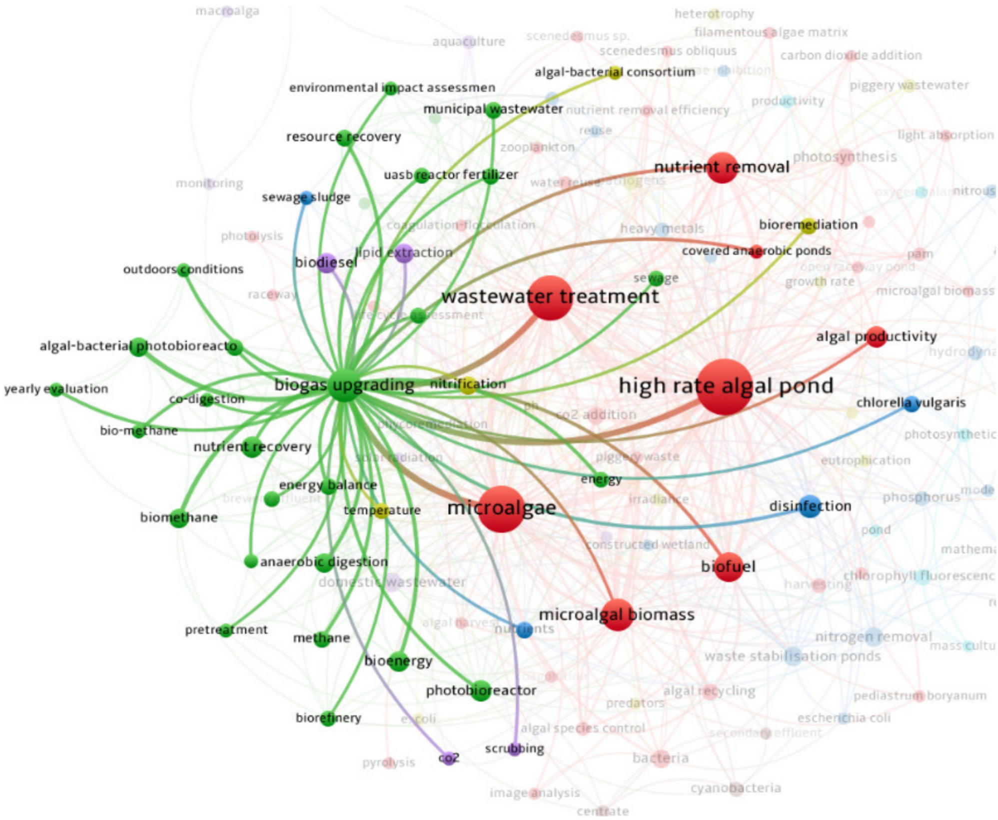
Figure 5. *Cont.*



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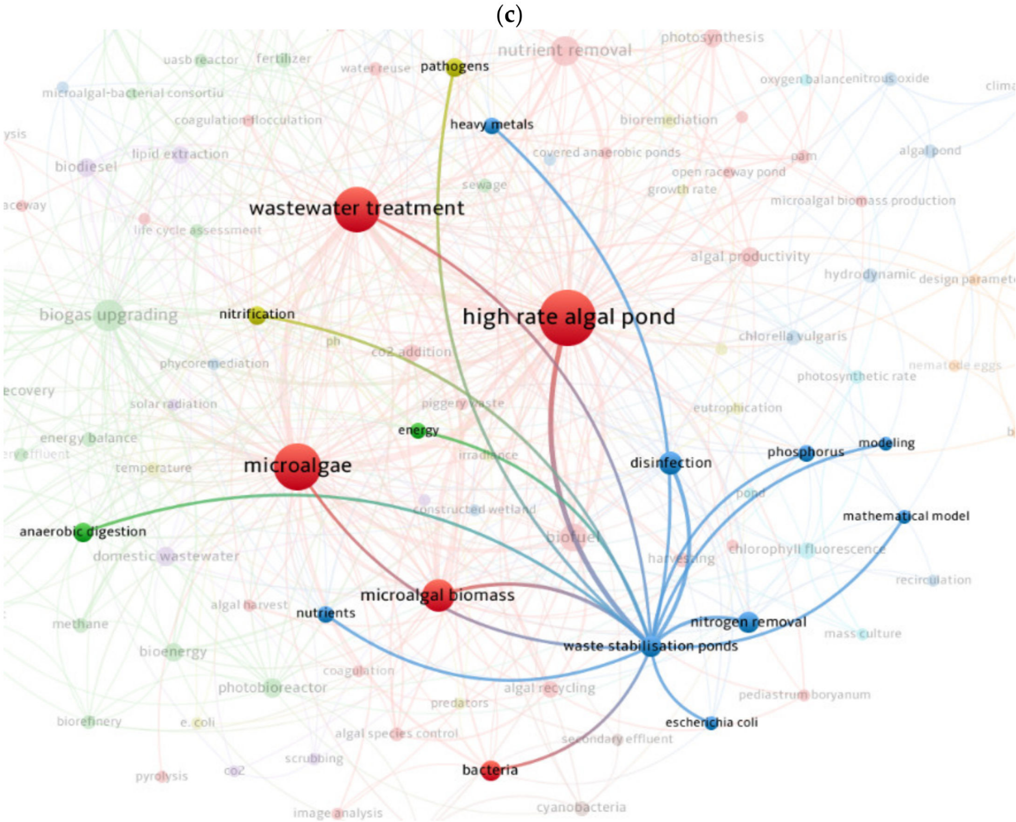

(**d**)

Figure 5. (**a**) co-occurrence network map of keywords; (**b**) selection of terms in the bibliometric map: high-rate algal pond; (**c**) biogas upgrading; (**d**) waste stabilization ponds.

As seen in Figure 5, the largest cluster is the red cluster, which is the largest node in this study because the retrieved keyword is HRAPs. In addition, the main keywords of the red cluster are "wastewater treatment", "nutrient removal", "microalgal", "microalgal biomass", and "biofuel". It indicates that the main research in the red cluster is on using microalgae to treat wastewater. More studies are related to removing ammonia and nitrogen while harvesting algal biomass. Therefore, HRAPs remove organic nutrients while harvesting algae/bacterial biomass [44,45] and producing biofuels [46] main research directions. Furthermore, as far as the operational parameters of HRAPs in the treatment of wastewater are concerned, they mainly contain initial nutrient loading, culture depth, and hydraulic retention time (HRT) [47]. Among these, initial nutrient loading has an impact on HRAPs' nutrient removal efficiency and biomass production. The culture depth, usually in the range of 0.2–0.45 m, is a key operational characteristic of HRAPs and determines the degree of light attenuation. HRT is one of the crucial operational parameters for HRAPs as it influences the water quality of the discharged effluent and thus determines the limit of nutrient loading in the wastewater influent.

An analysis of the green cluster shows that it covers two areas of research, the first of which is related to "biogas upgrading", with keywords such as "biomethane", "biorefinery", "anaerobic digestion", and "co-digestion", et al. The research demonstrates that upgrading photosynthetic biogas in conjunction with "algae/bacteria" wastewater treatment is a promising technology for producing high-purity biomethane and treating water [48].

The blue cluster focuses on the keywords "waste stabilization ponds (WSPs)" and "disinfection". HRAPs crush many disadvantages of WSPs, such as poor and highly variable effluent quality and limited removal of nutrients and pathogens [49] et al., thus providing advanced wastewater treatment results [1,50]. After the 1990s, mechanical models began to dominate due to the rapid development of computer technology and the increased understanding of the underlying mechanisms in ponds. For instance, some mechanistic models integrate pathogen elimination with CFD [51–53]. It indicates that scholars are increasingly interested in simulating optimal design analysis in HRAPs [54].

Other clusters include the purple cluster "domestic wastewater", "lipid extraction", "solar radiation", and "scrubbing"; the yellow clusters "nitrification", "eutrophication "and "heterotrophy"; and the blue clusters "chlorophyll fluorescence", "photosynthetic rate" and "bioremediation". On the other hand, smaller nodes in the graph or keywords not shown can identify research gaps in the field. The keywords "low carbon", "carbon neutral", "greenhouse gas emissions", "techno-economic analysis" and "economic analysis" are of low relevance in this field of study. Therefore, in future research, environmental impact reduction should be considered. While wastewater treatment HRAPs offer a number of environmental benefits over conventional facultative wastewater ponds, there are still some negative environmental impacts from HRAPs. Operational considerations may help minimize these. Moreover, the absence of keywords related to policy and social aspects in Figure 5 further highlights the urgent need for government policies and regulations in this area of research to develop and support the use of low-cost HRAP systems to effectively treat different types of wastewater to achieve affordability and sustainability.

3.6. Research Hot Trend Analysis

The co-occurrence of the terms during the past five years (from 2017 to 2021) was studied, making it easier to grasp the hot themes of the present study and future directions. In the end, 178 nodes and 841 connections were discovered, and the network density was 0.0534. The log-likelihood rate (LLR) algorithm was used to cluster the keywords, and the modularity Q value was 0.8649 > 0.3, indicating a significant clustering structure. A good grouping was indicated by the mean silhouette value of 0.9466 > 0.5. Finally, as illustrated in Figure 6 clustering, seven HRAPs' research hotspots were discovered.

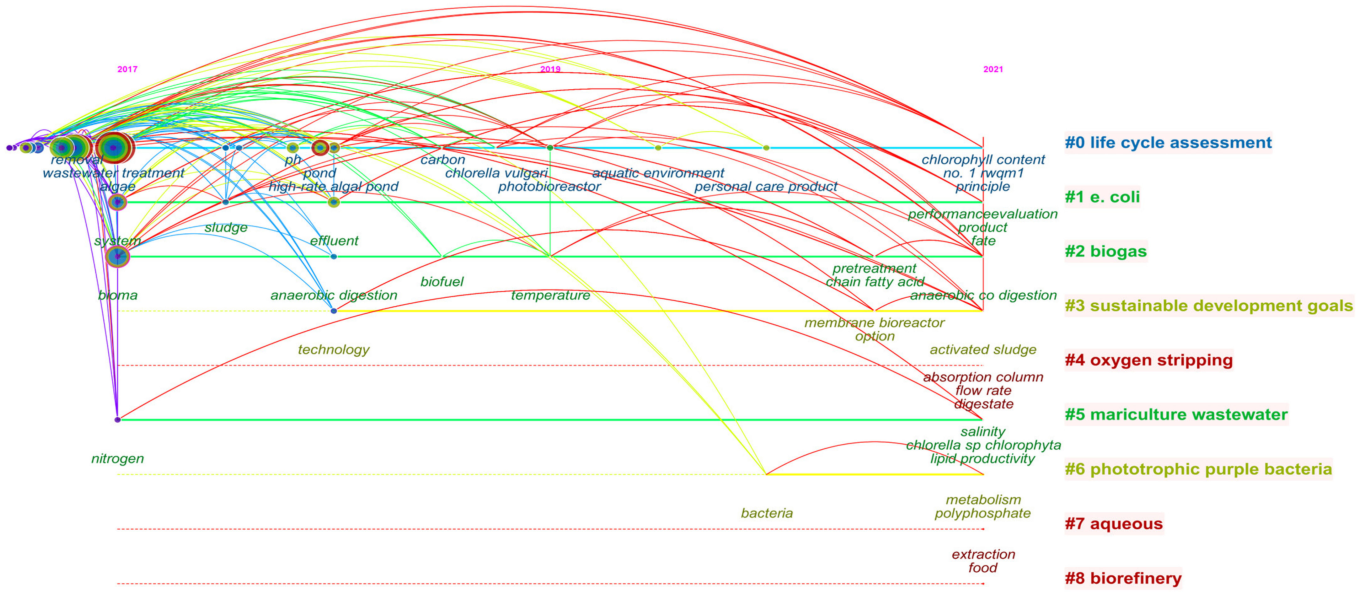

Figure 6. The keywords timeline view from 2017 to 2021.

Cluster #0 life cycle assessment and cluster #3 sustainable development goals indicate that current researchers in the field of HRAPs' research are more concerned with environmental, economic, and overall sustainability aspects through the LCA approach. For the post-treatment of UASB wastewater, HRAPs are viewed as a sustainable method [55]. By conducting a complete life cycle and cost analysis of HRAPs' wastewater treatment system and the value of enhancing harvested algal biomass, Young Kit Leong et al. demonstrated that HRAPs use less energy to treat wastewater than traditional activated sludge systems while producing microalgae that can be utilized to make non-food bioproducts and biofuel [11,56]. The HRAPs' technique is a feasible way to combine wastewater treatment with the development of microalgae biomass. Consequently, a crucial element of affordable and environmentally friendly waste management is using algae [57]. In addition, efficient resource recovery of wastewater, affordable construction, and low energy consumption must be achieved. This requires optimization and innovation in HRAPs' system design. Photoautotrophic algae systems have been studied as potential greener and more sustainable alternatives to conventional bacteria-based wastewater treatment (WWT) systems [58]. Using 30 process parameters from the sustainable development goals (SDGs) of the United Nations, Kanchanamala Delanka-Pedige et al. [59] compare wastewater infrastructure systems based on algae and activated sludge to evaluate their sustainability from environmental, economic, social, and all-around perspectives. These parameters enabled the multi-criteria decision-making approach to be applied in this comparison under three different sustainability aspects and 12 different scenarios/priorities. In most cases, the emergent mixotrophic algal system ranked as the most preferred one, followed by the membrane bioreactor. Kohlheb et al. [60] also reported that HRAPs' technology only requires 22% of the conventional system's energy consumption (0.1 vs. 0.45 kWh/m^3 wastewater), thereby being more energy-efficient. In addition, HRAPs performed better in terms of both economic feasibility (0.18 vs. 0.26 €/m^3 wastewater) and environmental friendliness (in the eutrophication and global warming potential categories).

Cluster #1 *E. coli* is one of the important biological indicators of fecal sewage pollution and water disinfection. It reflects the degree of bacterial contamination of the water body, usually used to evaluate the degree of water cleanliness and assess the water purification effect [61]. Recent research has demonstrated that HRAPs effectively remove *E. coli* from urban wastewater. Paul Chambonniere [62] et al. conducted two consecutive years of supplied domestic wastewater ($4.74 \cdot 106 \pm 3.37 \cdot 106$ MPN·100 mL^{-1}, N = 142, influent *E. coli* cell count) in two outdoor pilot-scale HRAPs (0.88 m^3) and found that the first-order decay rate of *E. coli* ranged from 3.34 to 11.9 d^{-1} (25–75% data range, N = 128) [62]. HRAPs can be naturally disinfected [10,63–67]. Its treated effluent standard can remove viral and bacterial indicators [68] to acceptable levels for subsurface irrigation of non-food crops [69]. Sherif Abd-Elmaksoud et al. showed that HRAPs could effectively oxidize wastewater organic compounds, increase nutrient removal, and remove pathogens and indicators. The approach described here reduced bacterial indicators by 5.6 log10, and viral indications were removed by 0.88 to 1.65 log10. The average clearance of the Giardia intestinalis and Cryptosporidium genes was 2.42 log10 and 0.52 log10, respectively. Interestingly, the integrated system eliminated parasitic helminth ova from the treated effluent, indicating that the method can safely lower pathogen exposure for people [70].

Cluster #2 biogas and #4 oxygen stripping indicate that current researchers are more concerned about biogas quality improvement and mitigation of oxygen pollution in biogas. The effectiveness of photosynthetic biogas extraction combined with wastewater treatment in an HRAPs system was evaluated by Mara del Rosario Rodero et al. They examined the impacts of the biogas flow rate, liquid-to-gas ratio (L/G), wastewater type (domestic wastewater vs. concentrate), and hydraulic retention time (HRT) in HRAPs on the biomethane quality [71]. It was demonstrated that at the L/G maximum, the removal efficiency (REs) of CO_2 and H_2S was at its best because there was a larger biogas–liquid mass transfer in the presence of a higher liquid flow. The findings demonstrated that wastewater type and biogas flow rate had less of an impact on the efficiency of biogas upgrading (more significant CO_2 and H_2S may be removed using concentrates due to the higher pH and alkalinity of the wastewater). Even though larger L/G ratios facilitate more significant CO_2 and H_2S removal, correspondingly greater N_2 and O_2 removal may result in inferior biomethane quality [71]. A further eco-friendly and more effective biogas upgrading method is HRAPs connected to an absorption bubble column (ABC), which combines microalgae and bacterial technology. The aerobic photosynthesis of microalgae in the extracted biogas is contaminated with oxygen because dissolved oxygen is lost from aqueous microalgae cultures, which restricts potential applications of the biogas [72]. Therefore, several strategies are proposed to facilitate oxygen desorption and absorption in the lifting system components and accessories.

Cluster #5 is mariculture wastewater. A large-scale, intensive aquaculture process will produce nitrogen, phosphorus, and other pollutants in wastewater [73]. Improper disposal is likely to lead to severe pollution of the surrounding water bodies and other environmental media, posing potential threats to the water environment and ecological security of the watershed. Nitrogen and phosphorus in the water body can be converted by microalgae into organic compounds while also producing oxygen [74]. In recent years, research has shown the potential of aquaculture wastewater as a nutrient substrate for microalgae cultivation. Research on treating mariculture wastewater by HRAPs has mainly focused on nutrient removal [75] and the production of microalgal biomass or the screening of dominant algae [76]. The microalgal biomass produced from aquaculture wastewater has high lipid, carbohydrate, and protein yields, which is advantageous for biofuel and feed applications. By entirely using the linkages between the conversion of energy and materials in the water environment, HRAPs' technology thus offers a novel technological solution for the purification of cultured water.

Cluster #6 is phototrophic purple bacteria. Due to their capacity for photoheterotrophic development in anaerobic conditions, phototrophic purple bacteria (PPB) are of interest [77]. PPB is a varied anaerobic, phototrophic, and parthenogenic anaerobic bacteria that use light as an energy source and can effectively absorb carbon and nutrients, increasing the recovery of these resources as various value-added products [77]. Consequently, there is growing interest in the application of wastewater resource recovery, particularly in the photoheterotrophic growth mode of mixed culture [78–81]. Future HRAPs' research could explore the potential of biological treatment employing such phototrophic bacteria as an affordable and ecologically friendly option.

Cluster #7 is aqueous. The conversion of all or a portion of algal biomass via various processes, such as fermentation, esterification, anaerobic digestion (AD), pyrolysis, and hydrothermal liquefaction, could result in a variety of liquid biofuels (HTL) [82]. Among all the algal transformation methods, HTL has received extensive attention due to its lack of feedstock dehydration, the fact that the majority of products were self-separated, and the high potential of the HTL aqueous phase to be recycled into the pond [50,83–86].

Cluster #8 is biorefinery. With the appropriate conversion technology, biorefineries offer a sustainable way to generate various bioenergy products from different biomass feedstocks. Microalgal biomass is an excellent source of feedstock for creating biodiesel, biomaterials, and biofuels. The biofuel business has substantially benefited from using microalgae biomass resources, such as microalgae or altered microalgae, in manufacturing bio-based products, particularly biodiesel and biomass oil. It has also opened up new technological paths for the bioenergy sector. The use of microalgae as a third-generation biofuel feedstock in biorefineries is currently gaining more attention [87]. The manufacturing of microalgae-based biofuel has become more expensive in recent years, and biorefining has gained attention as a potential solution. The notion of the circular economy will help attain sustainable development goals through economically advantageous biorefining microalgae.

4. Conclusions and Prospects

HRAPs are an efficient, sustainable, and environmentally friendly wastewater treatment method that was designed to reduce waste, minimize logistical costs, and promote wastewater recycling and resource recovery from the water environment. In this study, a bibliometric analysis of HRAPs' research articles in the WOS database was conducted, and knowledge maps were obtained through information visualization tools. The following conclusions were drawn: The overall number of publications has increased rapidly since 2013, which indicates that this research area has attracted a lot of attention from relevant scholars in the last decade. Spain, New Zealand, and Australia were the most productive countries and played important roles in this field. A relatively complete system of collaboration has developed between research institutions and authors. Of these, NIWA, Univ Valladolid, and Massey Univ were the top three institutions with the highest number of published articles. The top three authors with the most published papers were Craggs, R.J., Munoz, R., and Ferrer, Ivet. *Water Science and Technology*, *Algal Research Biomass Biofuels and Bioproducts,* and *Bioresource Technology* were the most published journals. Through the keywords cluster analysis, life-cycle assessment, SDGs, biogas, mariculture wastewater, biofuel, and biorefinery are the hot research directions.

Future research should improve the theoretical and applied research on HRAPs' technology. Suggested concerns include: using multi-omics joint analysis such as macrogenomics, metabolomics, and transcriptomics to reveal the mechanism of microalgae decontamination; searching for key genes; focusing on inter-algal as well as population sensing studies between algae and bacteria; and screening for algal species with high decontamination capacity and high additive production value. Consider not only the effect of nitrogen and phosphorus removal but also the ability to remove pollutants such as heavy metals and antibiotics, thus improving the breadth and stability of HRAPs' applications. Development of cost-free or low-cost stable algal pond construction to optimize the purification conditions for HRAPs; Improve the efficiency of microalgae biomass collection and its high-value-added utilization methods to realize the combination of pollution treatment and resource utilization, forming an environmentally friendly and green high-value industrial cycle chain.

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