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Systematic Review

Bioprospecting Microalgae: A Systematic Review of Current Trends

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Abstract: The growing interest in microalgae is driven by their potential in various bioindustries, such as biofuel production, bioremediation, and the generation of high-value biomolecules. This paper aims to systematically review the state of research on bioprospecting microalgae, their applications, and recognize trends. This study employs an exploratory and descriptive research approach, using bibliometric methods to analyze scientific production and identify emerging trends in bioprospecting microalgae research. The analysis reveals exponential publication growth, with multidisciplinary sources indicating a strong applied focus. Leading countries in this research field benefit from clear technology transfer policies, and the prevalent terms "production" and "biomass" underscore the industrial relevance. Key research areas include biofuels and bioremediation, with a combined emphasis that is often studied in cultivation and biomass production. Bioactive compounds derived from microalgae are a current trend for industrial, medical, and food applications. Although the potential for CO_2 capture is acknowledged, direct studies are limited. This systematic review provides a comprehensive overview of current trends and identifies opportunities and challenges in microalgae research, highlighting its significance for sustainable development and industrial applications.

Keywords: biotechnology; bioremediation; biofuels; biomolecules; carbon fixation; food technology

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1. Introduction

Microalgae include a wide range of unicellular and colonial photosynthetic microorganisms from different taxonomic groups, such as Cyanobacteria or blue-green algae, Chlorophyta (green algae), Bacillariophyta (diatoms), Dinophyta (dinoflagellates), Haptophyta (coccolithophores), etc. [1–4]. These organisms are characterized by their microscopic size, typically ranging from a few microns to a few hundred microns, and their ability to perform photosynthesis using chlorophyll a and b or other photosynthetic pigments such as phycobiliprotein in the case of Cyanobacteria. The diversity of shapes and sizes of microalgae ranges from spherical cells to complex filamentous forms and multicellular colonies [5–7]. These characteristics confer microalgae vast potential for industrial applications and for producing several different metabolites [8].

Microalgal diversity has increasingly drawn attention to pursuing biological resources applicable to bioindustries. Therefore, microalgae have emerged as a promising source of biomolecules and biotechnology due to their high lipid content, secondary metabolite generation, and adaptability. The bioprospecting of microalgae has gained traction recently, driven by the necessity for sustainable solutions in energy, food, environmental restoration, and CO_2 capture technology, among others [9–13]. Indeed, microalgae cultivation faces significant challenges; however, its potential has enabled these challenges to be gradually overcome. These challenges include optimizing cultivation conditions, developing efficient harvesting techniques, and mitigating environmental contaminants. Additionally, production's economic feasibility and scalability are key aspects to consider. Nevertheless,

ongoing research and technological innovation are paving the way to fully harness the potential of microalgae [14–20].

Specifically, microalgae have gained particular interest in some biotechnological applications. Biofuel production is one of the most wanted applications for microalgae, mainly due to the growing demand for renewable energy and the imperative to mitigate greenhouse gas emissions [21–25]. Bioremediation application is another technology widely studied for microalgae because of their ability to absorb, accumulate, and metabolize contaminants, which is why they have been used in wastewater [26–29]. On the other hand, their capability to produce biomolecules with pharmaceutical, cosmetic, and nutritional value has spurred biotechnology research [26,30–33]. Numerous scientific articles, reviews, and books have demonstrated this progress, particularly in the last decade [24,31,34–37]. However, trend reviews might be atomized by the diversity of applications and species. Given the above, this paper aims to systematically review trends in applied studies of microalgae, focusing on diminishing the atomization of knowledge through the concept appropriation of "bioprospecting".

2. Materials and Methods

2.1. Exploratory and Descriptive Research

This study is framed within an exploratory and descriptive research approach, with a quantitative focus on analyzing the scientific production of microalgae cultivation and its various applications. Bibliometric methods were employed to identify trends, patterns, and emerging areas of interest in the scientific literature. This approach allows for a deeper understanding of the current state of research in the field of microalgae, as well as the identification of areas of opportunity and future challenges. Notably, the findings of this study have practical implications for the field, potentially guiding future research and development efforts. The methodology for the systematic review was slightly adapted from the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [38].

2.2. Search Strategy

Searches were conducted across three primary databases: Scopus [39], Web of Science (WoS) [40], and Lens [41]. The search strategy employed the following central equation: "All(microalgae AND (application OR industry OR innovation) AND bioprospecting)". Filters were applied to include only relevant studies. Results were quantified and classified by Document Type in any case. File exportation from databases was conducted on the 26 March 2024 cutoff. No time bias was considered in this study to completely comprehend trends through time.

2.3. Bibliometric Analysis

Bibliometric analysis was conducted using the Bibliometrix tool within RStudio [42]. The RStudio libraries Bibliometrix and openxls were utilized to process the data. The following commands were employed to unify and refine the information: setwd to set the working directory, convert2df to convert the data into a suitable format, and write.xlsx to export the results into an Excel file. Duplicates were excluded after unification. Analysis methods were executed using the default configuration in Bibliometrix [42]. No documents were excluded from the bibliometric analysis, but documents that did not directly treat microalgae were not considered for discussion.

- Scientific Annual Production: Analysis was conducted using default parameters across the overview, sources, authors, documents, conceptual structure, and social structure tools. Scientific Annual Production was graphed using Document Type information. Production was also contrasted by Country and Total Global Citation information.
- Analysis of sources: An analysis of sources was performed to understand trends and perspectives in the function of publications. Core sources by Bradford's Law from

Bibliometrix were executed to strengthen this analysis. WordCloud from Zygomatic was employed to complement this analysis graphically.

- The frequency of words across Title and Abstract information was determined to elucidate patterns and trends of topics and methods/processes, respectively. The term "microalgae" was removed for WordCloud graphs to clearly evidence trends. Complementary thematic maps were executed to determine the degree of relevance and development of knowledge about these topics. Both Keywords Plus and Author's Keywords were also used for thematic maps. A list of terms to remove and synonyms were loaded to refine these analyses.

2.4. Focused Analysis on Relevant Applications

Following the initial bibliometric analysis, a subsequent analysis focused on relevant applications was conducted. This analysis aimed to delve deeper into specific areas of interest related to microalgae. The applications considered included bioremediation, industrial and medical interest biomolecules, biofuels, food, and carbon fixation. These applications were incorporated into the search strategy using the Boolean operator AND with the central equation. The equations used for each application are detailed in Table 1. The same cleaning procedures were applied to this focused analysis. The thematic map was the only bibliometric analysis performed for these databases.

Table 1. Search Equations for Specific Applications.

Application	Search Equations
Bioremediation	All(bioremediation OR "waste water" OR wastewater OR biodegradation)
Industrial and Medical Interest Biomolecules	All(biomolecules OR drugs)
Biofuels	All(biofuel OR biodiesel OR energy OR bioenergy)
Food	All(food OR protein)
Carbon Fixation [1]	All((carbon OR CO_2 OR "carbon dioxide") AND (fixing OR fixation OR absorption OR sequestration OR capture OR assimilation OR reduction OR incorporation))

[1] The equation for searching studies related to carbon fixation is extensive due to the various terms used in the scientific literature to describe this process. This wide range of terms aims to ensure the inclusion of relevant studies addressing different aspects of carbon fixation in microalgae.

The results were documented and exported into Excel files for further examination and interpretation.

2.5. PRISMA Flow Diagram

The employed methodology is illustrated in Figure 1.

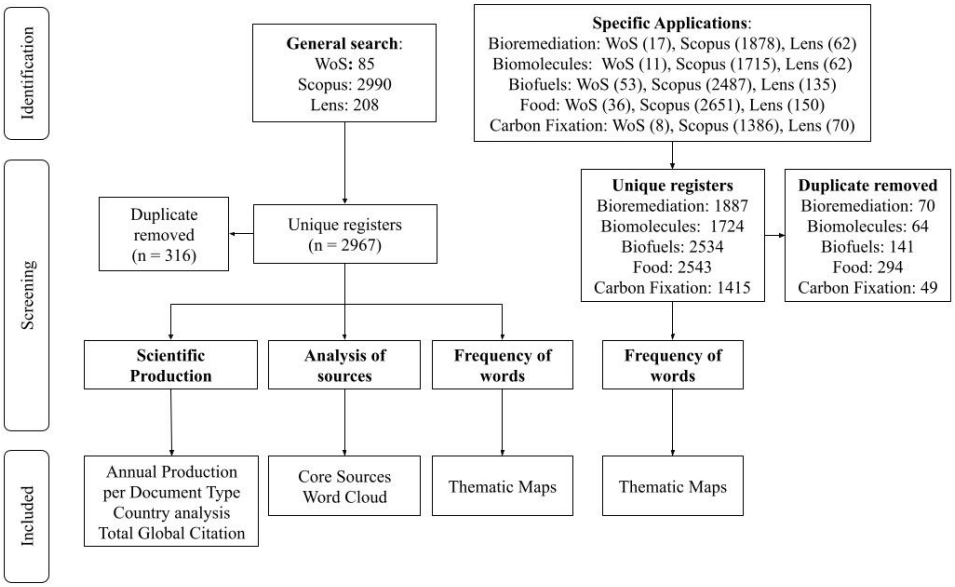


Figure 1. PRISMA Flow Diagram.

2.6. Data Collection and Storage

Raw files from WoS, Scopus, Lens, Bibliometrix files, and lists of terms of specific applications were stored as a Zenodo record [43]. This data collection also included a list of synonyms and terms to remove in Bibliometrix analyses.

3. Results and Discussion

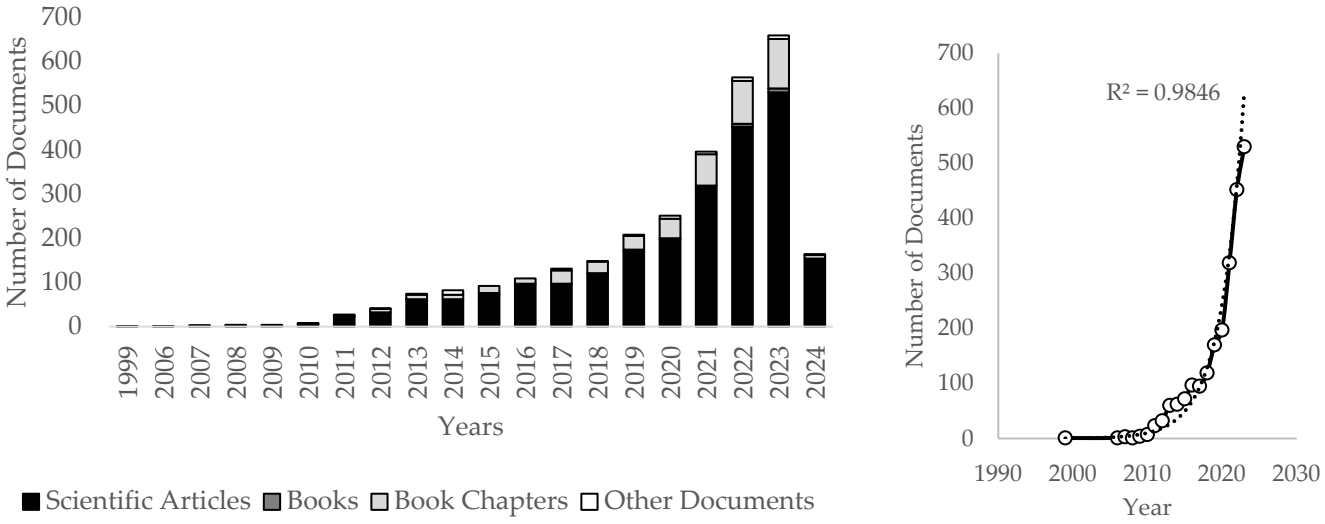
3.1. General Search

From the central equation, the following documents were retrieved:

- Scopus: 2990
- Web of Science (WoS): 85
- Lens: 208

After the unification and removal of duplicates, 2967 reviewed documents were obtained using Bibliometrix (Figure 2a). Scientific annual production has been rapidly increasing over the years. Scientific articles, including reviews and research articles, demonstrate exponential growth in their annual production (Figure 2b). Although bioprospecting is an ancient concept by definition, its use has been relatively recent, emerging in the 1990s and progressively growing over time [44]. The results of this search are consistent with the global appropriation of this concept, and differences among databases can be explained because of a potential concept bias that could strongly restrict this search. In this sense, this study reflects trends in microalgae bioprospecting.

A total of 838 sources were compiled from this search, of which only 50 sources (6% of total sources) are specific to phycology or direct reference to algal applications. The terms “science”/”sciences” are the most frequent in the name of total sources with 95 repeats in sum, followed by the term “biotechnology” with 89 repeats, then “microbiology”/”microbial” with 79 repeats in sum, then “research” with 63 repeats, and then both “environmental” and “food” with 55 repeats. Consequently, terms such as “engineering”, “technology”, “sustainable”, “applications”/”applied”, “chemistry”, and “energy”, among others, are still present. WordCloud shows trend applications through sources’ names (Figure 3).



(**a**) (**b**)

Figure 2. Annual Scientific Production from central search equation: "All(microalgae AND (application OR industry OR innovation) AND bioprospecting)": (**a**) Annual Scientific Production by Document Type; (**b**) behavior trend for Annual Scientific Production.

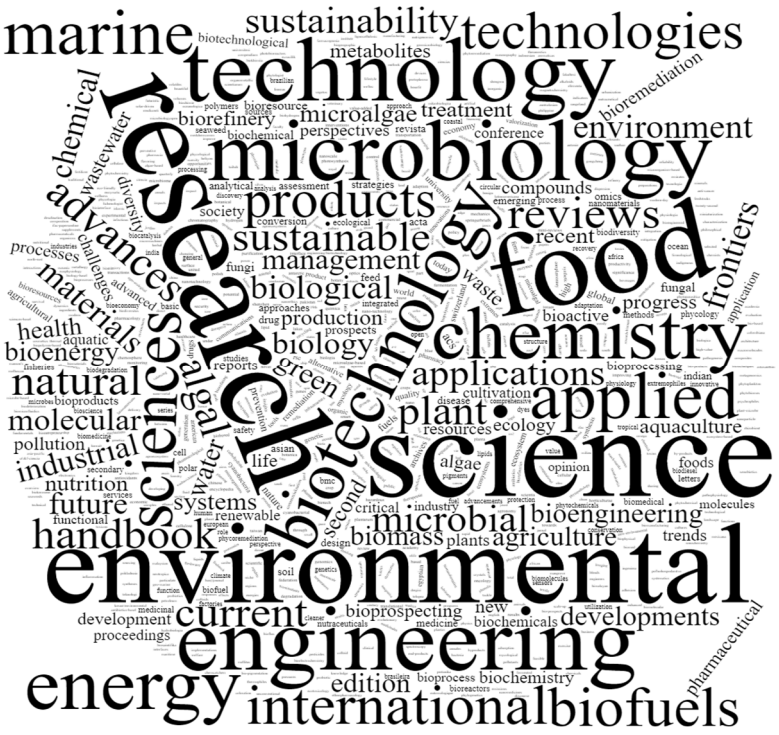


Figure 3. WordCloud of total source names from the central search equation database.

A list of core sources was constructed using sources of zone 1 from core sources by Bradford's Law of Bibliometrix (Table 2). Thirty sources were tabulated with specific information about the Platform Publisher, thematic specificity (SP), rank of core sources by Bradford's Law (CS), H-index (H), G-index (G), M-index (M), number of total citations (TC), number of publications (NP), and the year when sources started to publish on the themes of this study (PY). Two sources were considered specific for phycology or direct reference to algal applications: *Algal Research* from ScienceDirect: ELSEVIER and *Journal of Applied Phycology* from Springer Link. Thirteen sources were constituted by journals from

ScienceDirect: ELSEVIER, followed by MDPI (7) and Springer Link (6). The source with the highest H is *Bioresource Technology* (51), followed by *Algal Research* (38) and *Renewable and Sustainable Energy Reviews* (30). The same order is observed with *M*. For G, the third place is occupied by *Marine Drugs*. Concerning TC information, *Bioresource Technology* also reached the first rank with 8196 citations, followed by *Renewable and Sustainable Energy Reviews* with 4714 citations and *Algal Research* with 4420 citations. Finally, regarding NP, *Bioresource Technology* and *Algal Research* reached first place with 140 publications each, followed by *Marine Drugs* with 77 publications. This analysis demonstrates that phycology functions as an applied science, in which knowledge is transferred across various applications, but there is a need for further development within its primary discipline.

Table 2. List of core sources according to Bradford's Law.

Source	Platform Publisher	SP	CS	H	G	M	TC	NP	PY
Algal Research	ScienceDirect: ELSEVIER	SP.	1	38	61	2.923	4420	140	2012
Bioresource Technology	ScienceDirect: ELSEVIER	NSP.	2	51	87	3.643	8196	140	2011
Marine Drugs	MDPI	NSP.	3	24	50	2	2563	77	2013
Journal of Applied Phycology	Springer Link	SP.	4	20	30	1.667	1037	57	2013
Renewable And Sustainable Energy Reviews	ScienceDirect: ELSEVIER	NSP.	5	30	37	2.5	4714	37	2013
Molecules	MDPI	NSP.	6	15	30	1.875	917	36	2017
Science of The Total Environment	ScienceDirect: ELSEVIER	NSP.	7	17	33	2.429	1127	33	2018
Biomass Conversion and Biorefinery	Springer Link	NSP.	8	7	9	2.333	127	32	2022
Frontiers in Microbiology	Frontiers	NSP.	9	9	24	1	599	26	2016
Microorganisms	MDPI	NSP.	10	9	20	1	433	25	2016
Bioenergy Research	Springer Link	NSP.	11	11	23	0.917	655	23	2013
Bioresource Technology Reports	ScienceDirect: ELSEVIER	NSP.	12	9	13	1.5	187	23	2019
Chemosphere	ScienceDirect: ELSEVIER	NSP.	13	12	22	2.4	637	22	2020
Scientific Reports	Nature	NSP.	14	10	16	1	283	22	2015
Biotechnology Advances	ScienceDirect: ELSEVIER	NSP.	15	15	21	1.5	1650	21	2015
Environmental Science and Pollution Research	Springer Link	NSP.	16	10	20	1	428	21	2015
Renewable Energy	ScienceDirect: ELSEVIER	NSP.	17	13	21	1.083	834	21	2013
Journal of Cleaner Production	ScienceDirect: ELSEVIER	NSP.	18	14	20	2	1095	20	2018
Applied Sciences (Switzerland)	MDPI	NSP.	19	9	16	1.5	266	19	2019
Fuel	ScienceDirect: ELSEVIER	NSP.	20	9	19	1.5	440	19	2019
Applied Biochemistry and Biotechnology	Springer Link	NSP.	21	11	18	0.846	499	18	2012
Biomass And Bioenergy	ScienceDirect: ELSEVIER	NSP.	22	13	18	1.083	457	18	2013
Foods	MDPI	NSP.	23	8	14	1.6	211	18	2020
Biocatalysis and Agricultural Biotechnology	ScienceDirect: ELSEVIER	NSP.	24	7	17	0.583	307	17	2013
International Journal of Hydrogen Energy	ScienceDirect: ELSEVIER	NSP.	25	11	17	1.222	320	17	2016

Table 2. *Cont.*

Source	Platform Publisher	SP	CS	H	G	M	TC	NP	PY
Journal of Chemical Technology and Biotechnology	Wiley	NSP.	26	8	14	0.615	218	17	2012
3 Biotech	Springer Link	NSP.	27	7	14	0.7	196	16	2015
Critical Reviews in Biotechnology	Taylor & Francis Online	NSP.	28	11	16	0.917	671	16	2013
Energies	MDPI	NSP.	29	10	16	0.769	505	16	2012
International Journal of Molecular Sciences	MDPI	NSP.	30	8	16	0.8	433	16	2015

"SP" is thematic specificity. "SP." is specific to the theme of this study. "NSP." is non-specific for the theme of this study. "CS" is the rank of core sources by Bradford's Law. "H" is the H-index. "G" is the G-index. "M" is the M-index. "TC" is the number of total citations. "NP" is the number of publications. "PY" is the year when sources start to publish on the theme of this study.

From the constructed database, scientific production per country was also observed (Figure 4, Table 3). India had the highest number of publications, coherently with the highest number of total citations. China and the USA follow it. These results demonstrate the authority of research teams in India, China, and the USA, likely due to robust or active research community, investment, or even technology transfer and commercialization models and policies' presence [45]. Interestingly, Brazil occupies fourth place and is the only country in the Latin American region that ranked highly in this analysis. Brazil's prominent position indicates that it is a key player and leader in scientific research within its region, contributing significantly to Latin American research output and influence [46]. Four European countries are in this list of the countries with the highest scientific production in this area. The presence of multiple European countries in the top ranks signifies the continent's strong tradition of research excellence. These countries often lead in various scientific fields and foster cross-border collaboration, further enhancing their authority and impact.

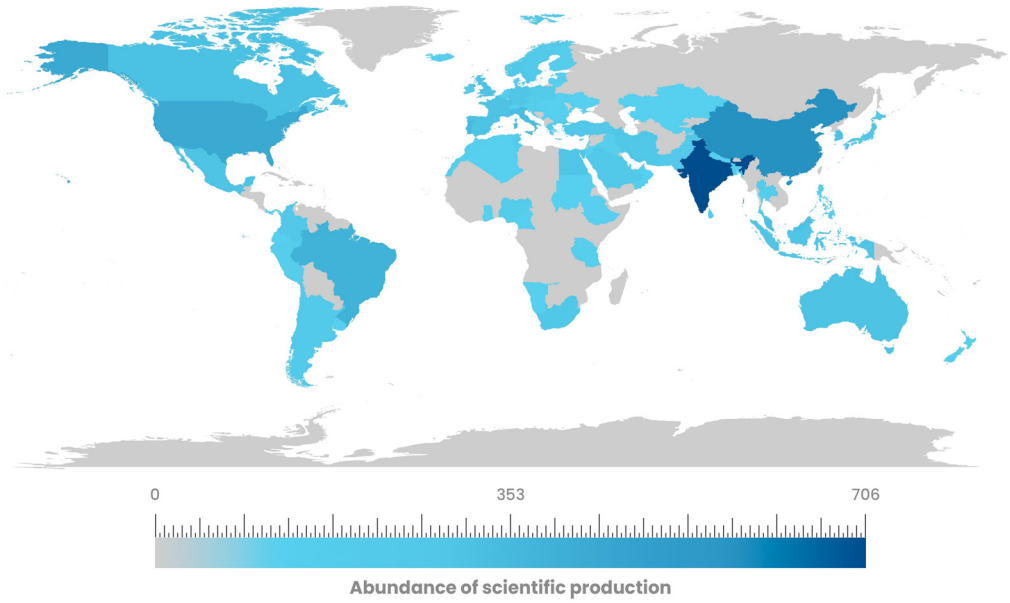


Figure 4. Density map of the world's scientific production according to the database resulting from the central search equation: "All(microalgae AND (application OR industry OR innovation) AND bioprospecting)". The blue scale demonstrates the abundance of scientific production. The gray color demonstrates the absence of information about scientific production.

Table 3. Top 10 countries by number of publications.

Country	NP	TC
India	706	10,363
China	319	9085
USA	198	7564
Brazil	153	3153
Portugal	108	2059
Italy	89	1615
Malaysia	75	2002
Canada	74	2582
South Korea	74	2144
France	65	1897

"NP" is the number of publications. "TC" is the total citations.

Ten references from the explored database were chosen to elucidate interesting trends through citations (Table 4). This analysis reveals that older papers have seen a decline in their annual citation rate (TC per Year), undoubtedly due to their age. However, despite being less aligned with current trends, their presence in the top 10 underscores their enduring relevance in the field. Their reduced citation rate may reflect a shift towards newer research directions, but their inclusion in this list demonstrates their significant and ongoing contribution to the discipline. Taylor et al. (2007) [47] reached the highest number of global citations, followed by two publications by the same first author: Rawat et al. (2011) [48] and Rawat et al. (2013) [49]. Particularly, Sathasivam et al. (2019) [50] demonstrated to be the publication with the highest number of total citations per year and the highest number of normalized total citations, followed by Li et al. (2019) [34] and Kumari and Singh (2018) [35]. The bibliometric review uncovered a diverse and significant collection of highly cited articles addressing pertinent biotechnology and environmental engineering topics. The selected top ten articles span many areas, ranging from wastewater treatment to biofuel production and exploration of microorganisms associated with marine sponges. These topics reflect a growing interest in sustainable solutions to environmental challenges and the biotechnological potential of microscopic organisms. In recent years, there has been a noticeable surge in research regarding the use of microalgae for wastewater treatment and nutrient recovery [34,51]. This trend aligns with the escalating concerns over water resource scarcity and the imperative to find sustainable alternatives to conventional wastewater treatment methods.

Furthermore, integrating CO_2 capture, wastewater treatment, and biofuel production through microalgae cultivation has emerged as a promising research avenue [51]. This multifunctional approach addresses climate change mitigation and the quest for renewable energy sources. Research into using lignocellulosic wastes for biofuel production has garnered attention due to its potential to reduce dependence on fossil fuels [35]. There has been particular interest in developing more efficient and cost-effective pretreatment methods and optimizing biomass conversion processes. This focus reflects a heightened awareness of the importance of utilizing renewable and sustainable resources in energy production.

Additionally, investigation into microorganisms associated with marine sponges has unveiled vast biotechnological potential in producing bioactive metabolites [47]. This emerging field offers opportunities for developing new pharmaceutical products and biofuels and studying microbial diversity in aquatic ecosystems. These themes underscore a shift towards more integrated and sustainable approaches in biotechnology and environmental engineering, emphasizing harnessing natural resources and minimizing environmental impact.

Table 4. Top 10 documents with the most global citations.

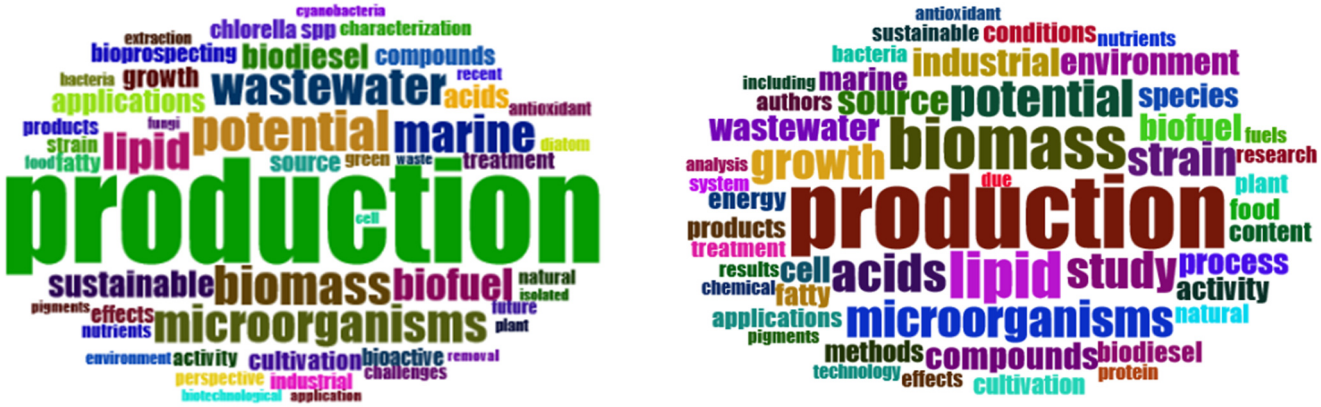
Paper	Source	TC	TC per Year	Norm. TC
Taylor et al., 2007 [47]	Microbiology and Molecular Biology Reviews	1083	60.17	2.52
Rawat et al., 2011 [48]	Applied Energy	876	62.57	7.09
Rawat et al., 2013 [49]	Applied Energy	750	62.50	8.86
Georgianna and Mayfield, 2012 [52]	Nature	588	45.23	6.64
Günerken et al., 2015 [53]	Biotechnology Advances	527	52.70	7.44
Sathasivam et al., 2019 [50]	Saudi Journal of Biological Sciences	499	83.17	14.86
Kumari and Singh, 2018 [35]	Renewable and Sustainable Energy Reviews	485	69.29	11.12
Razzak et al., 2013 [51]	Renewable and Sustainable Energy Reviews	474	39.50	5.60
Li et al., 2019 [34]	Bioresource Technology	421	70.17	12.54
Martins et al., 2013 [54] [1]	Marine Drugs	395	35.91	7.51

"TC" is the total citations. "TC per Year" is the total citations per year. "Norm. TC" is normalized total citations. [1] In the bibliometric analysis for Most Global Cited Documents in Bibliometrix, two documents are higher in rank [55,56] than the chosen one [54] but do not directly treat microalgae topics. The database includes these references because they are connected to microalgae topics through their reference list or citations.

The perspectives addressed in the provided references shed light on various research areas on utilizing microalgae and other biological resources for wastewater treatment, biofuel production, and obtaining value-added products. There is an emphasis on seeking sustainable alternatives to address the water crisis and reduce dependence on fossil fuels. For example, Li et al. review the use of microalgae in wastewater treatment, highlighting the need for further research to optimize treatment processes [34]. Razzak et al. discuss CO_2 capture, wastewater treatment, and biofuel production through microalgae cultivation [51]. Kumari and Singh review pretreatment methods of lignocellulosic waste for biofuel production, emphasizing the importance of combined pretreatments [35]. Sathasivam et al. and Martins et al. describe bioactive compounds produced by microalgae and their relevance in the food and pharmaceutical industries [50,54]. Günerken et al. analyze cell disruption technologies for valuable chemical production from microalgae [53]. Georgianna and Mayfield discuss the potential of algae biofuels and the need for strain and process development [52]. Rawat et al. critically evaluate biodiesel production from microalgae, from laboratory trials to large-scale production [49], and propose the dual use of microalgae for wastewater phytoremediation and biomass production for sustainable biofuels [49]. Taylor et al. explore the diversity of microorganisms associated with marine sponges and their biotechnological potential [47]. These studies suggest a broad field of study and future development in environmental biotechnology and biofuel production from renewable sources.

The most frequent words across the Title and Abstract information were "production", "biomass", "lipid", "acids", "potential", "microorganisms", "growth", and "strain". Nevertheless, some differences were found regarding terms that appear in Title information and not in Abstract information, and vice versa. For Title information, words related to microalgae species, such as "chlorella spp", "green", "diatom", and "cyanobacteria"; words associated with bioprospecting methods, such as "bioprospecting", "bioactive", "characterization", "extraction", "removal", "application", "waste", and "biotechnological"; and words that refer review studies, such as "future", "perspective", and "challenges", were frequent and visualized in Figure 5a. The co-occurrence network defined "production" as the most frequent word after microalgae (Figure 6). For Abstract information, words related to applications, such as "process", "energy", "research", "fuels", "protein", and "technol-

ogy"; and words that mean method studies, such as "process", "methods", "conditions", "results", "system", and "analysis", were frequent and visualized in Figure 5b.



(**a**) (**b**)

Figure 5. WordCloud of the main search equation: "All(microalgae AND (application OR industry OR innovation) AND bioprospecting)" and generated from: (**a**) Title information; (**b**) Abstract information.

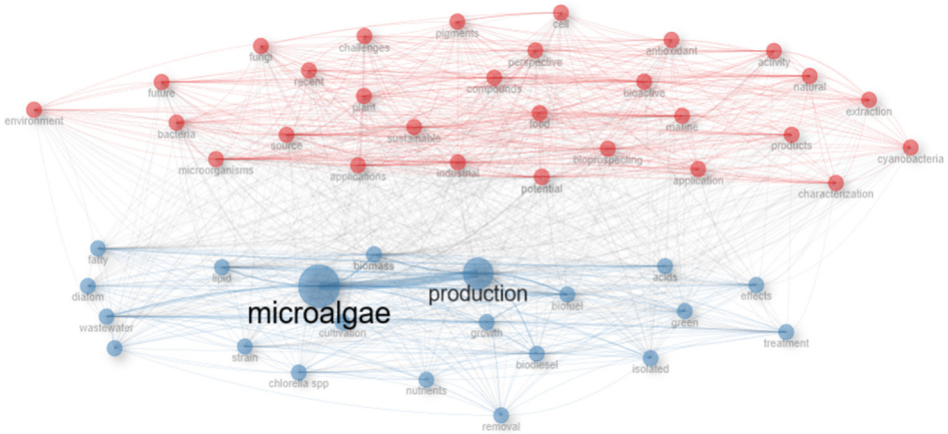


Figure 6. Co-occurrence network for "All(microalgae AND (application OR industry OR innovation) AND bioprospecting)" and generated from Title information.

The database's thematic maps were constructed using the general equation elucidated between 2 and 4 clusters based on Keywords Plus, Author's Keywords, Title, and Abstract information (Figure 7).

Keywords Plus information generated three clusters, which are detailed in Table 5 and as follows:

1. Microalgae, with a Cluster Frequency of 10.792, comprises simple/combined terms of specific microalgal biomass production studies for industrial applications such as biofuel, biodiesel, and bioremediation;
2. Nonhuman, with a Cluster Frequency of 5.994, comprises simple/combined terms of biological composition studies for biotechnological applications such as metabolic and genetic engineering, biochemistry, and synthetic biology. Other terms associated with ecological relationships or consortia applications are included in this cluster;
3. Human, with a Cluster Frequency of 2.996, comprises simple/combined terms of biological activity studies for biomedical or veterinary applications such as bioprospecting, antimicrobial and antioxidant activity, and drugs.

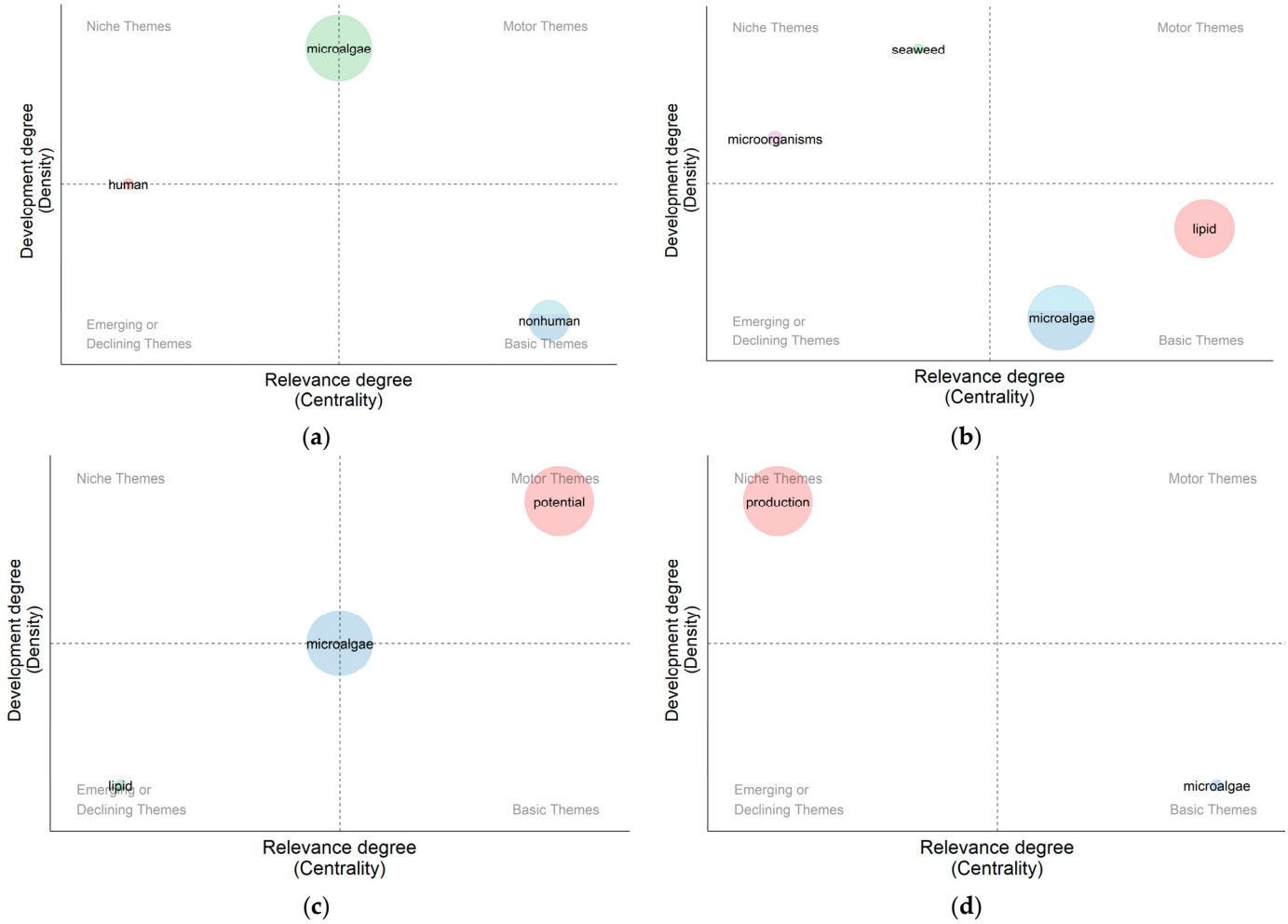


Figure 7. Thematic maps of the central search equation: "All(microalgae AND (application OR industry OR innovation) AND bioprospecting)" and generated from: (**a**) Keywords Plus information; (**b**) Author's Keywords information; (**c**) Title information; (**d**) Abstract information.

Table 5. Top 10 terms in generated clusters for Keywords Plus information.

Microalgae		**Nonhuman**		**Human**	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
microalgae	946	nonhuman	742	human	268
biomass	602	metabolism	378	animal	145
biofuel	427	biotechnology	226	antioxidant	126
lipid	332	bacteria	220	unclassified drug	183
microorganisms	536	controlled study	242	bioproducts	96
wastewater	215	chemistry	238	seaweed	68
fatty acid	264	cyanobacteria	127	polysaccharide	72
chlorella spp	217	carotenoids	131	biodiversity	77
biodiesel	269	fungi	97	astaxanthin	72
nitrogen	161	diatom	77	antioxidant activity	89

The Keywords Plus clusters, focusing on specific studies and applications, suggest a well-defined interest in practical, outcome-oriented research fields. This analysis includes industrial uses such as biofuel production and bioremediation, indicating a solid drive towards sustainability and environmental management. The higher Cluster Frequency in Keywords Plus for terms related to microalgal biomass production further emphasizes this practical application focus. Terms in cluster Microalgae comprise themes that are

currently considered publication trends. On the other hand, terms in cluster Nonhuman represent growing themes for research and are considered near-future trends for publication because of their high relevance and low development. Finally, terms in cluster Human are associated with emerging or declining publication themes. Considering that these keywords are extracted from the phrases frequently appearing in the titles of the cited references within the articles, terms in cluster Nonhuman are relevant to include in near-future publications to reach academic positioning.

For the Author's Keywords, four clusters were generated by Bibliometrix, which are detailed in Table 6 and as follows:

1. Microalgae, with a Cluster Frequency of 2.509, comprises simple/combined terms of biotechnological applications of microalgae, such as bioenergy and bioremediation;
2. Lipid, with a Cluster Frequency of 2.509, comprises simple/combined terms of bioprospecting studies such as bioactive compounds, metabolic engineering, and synthetic biology;
3. Microorganisms and Seaweed have similar Cluster Frequencies of 134 and 130, respectively. These clusters comprise a few terms with low impact in this study.

Table 6. Top 10 terms in generated clusters for Author's Keywords information.

Microalgae		Lipid		Microorganisms		Seaweed	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
microalgae	775	lipid	152	microorganisms	53	seaweed	49
biofuel	260	cyanobacteria	107	enzymes	21	bioactivity	23
biodiesel	198	fatty acid	106	heavy metals	21	lipidomics	22
biomass	125	carotenoids	89	phytoremediation	21	glycolipids	18
wastewater	97	antioxidant	81	biodegradation	18	phospholipids	18
biorefinery	90	bioactive compounds	69	metagenomics	14	mass spectrometry	14
bioremediation	79	bioprospecting	69	nanoparticles	14		
wastewater treatment	79	diatom	68	toxicity	14		
chlorella spp	73	pigments	54				
sustainability	55	astaxanthin	53				

The Author's Keywords clusters, which also highlight biotechnological applications and bioprospecting studies, suggest that researchers are particularly interested in microalgae's biochemical and genetic potential. Clusters related to lipids and other microorganisms imply a comparative approach, where microalgae are studied alongside other biological entities to uncover unique or superior traits. Terms in clusters Microalgae and Lipid represent growing themes for researchers and are considered trends of interest for research groups because of their high relevance and low development. Finally, terms in clusters of Microorganisms and Seaweed are associated with niche themes, implying that researchers frequently used them for their publications but that they have lost relevance over time. Trend terms in this analysis are congruent with Keywords Plus information, which elucidates coherence between trend publications among sources and authors.

Title information generated three clusters, which are described in Table 7 and are as follows:

1. Potential, with a Cluster Frequency of 6.381, comprises simple terms of potential and bioprospecting application of microalgae;
2. Microalgae, with a Cluster Frequency of 5.997, comprises simple terms of interested studies of perspective and trends and industrial processing application of microalgae and their production;
3. Lipid, with a Cluster Frequency of 1.930, comprises simple terms of culture and growth systems for several purposes.

Table 7. Top 10 terms in generated clusters for Title information.

Potential		Microalgae		Lipid	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
potential	281	microalgae	1088	lipid	242
microorganisms	254	production	686	growth	139
marine	249	biomass	265	cultivation	132
applications	156	wastewater	247	chlorella spp	121
acids	142	biofuel	218	effects	117
compounds	129	sustainable	180	nutrients	95
source	130	biodiesel	169	removal	81
fatty	120	treatment	117	enhancement	69
bioprospecting	122	industrial	108	culture	53
bioactive	113	future	95	optimization	52

Title information clusters reveal trends and industrial applications, suggesting that the titles of the research papers often emphasize the broader impact and potential future directions of the studies. This fact can indicate a strategic approach to framing research regarding its relevance to current scientific and industrial challenges. Terms in the Potential cluster comprise themes currently considered research trends. Terms in the Microalgae cluster represent growing themes of interest for researchers and are considered near-future trends among research groups because of their high relevance and low development. Finally, terms with emerging or declining trends are grouped in the Lipid cluster. Terms in clusters Potential and Microalgae must be considered in present and near future research projects.

Finally, the Abstract information generated two clusters, which are detailed in Table 8 and are as follows:

1. Production, with a Cluster Frequency of 56.387, comprises simple or combined terms associated with methods and processes of the microorganisms' bioproducts, with a broader focus on various applications and research areas.
2. Microalgae, with a Cluster Frequency of 27.138, comprises simple or combined terms around the study of microalgae and their potential uses, particularly in producing biodiesel and other biofuels.

Table 8. Top 10 terms in generated clusters for Abstract information.

Production		Microalgae	
Term	**Occurrence**	**Term**	**Occurrence**
production	1573	microalgae	1679
potential	1267	biomass	1066
microorganisms	740	lipid	800
source	976	acids	789
industrial	868	growth	999
compounds	721	strain	690
biofuel	613	wastewater	457
environment	825	cell	630
process	764	fatty	566
species	655	biodiesel	415

The abstract information, with its dominant clusters related to biotechnological applications and specific methodological approaches, shows a detailed methodological focus. Abstracts will likely delve into the techniques and procedures used in microalgae research, aligning with the high Cluster Frequency for terms related to sampling and extraction methods. This methodological emphasis in abstracts suggests that researchers prioritize sharing detailed processes and innovations in their methodologies, potentially to facilitate replication and further development by others in the field.

These different emphases reflect a comprehensive research approach, addressing the practical applications and the underlying scientific principles, thereby fostering a robust understanding and utilization of microalgae across various domains.

Focusing on practical applications, academic staff and researchers can directly contribute to biofuel production, environmental remediation, and industrial bioprocessing, driving immediate advancements in sustainable technologies. The emphasis on specific study areas ensures that applied research is grounded in solid empirical data, making the solutions viable and scalable. Concurrently, exploring biochemical and genetic aspects through the Author's Keywords indicates a deeper dive into the fundamental science of microalgae. This approach advances the basic understanding of these microorganisms and uncovers new possibilities for their use in synthetic biology, metabolic engineering, and the production of high-value bioproducts. By identifying and manipulating the genetic and metabolic pathways, researchers can enhance the efficiency and yield of desired compounds, leading to more effective and innovative applications [50,57]. Titles often highlight broader trends and potential impacts, suggesting a strategic vision that frames individual studies within the larger context of scientific and industrial advancements. This aspect helps attract attention and funding and aligns research efforts with global priorities, such as sustainability and green technology [58–60]. It reflects a forward-thinking perspective considering microalgae research's long-term implications and scalability. Abstracts, on the other hand, typically emphasize detailed methodologies and technical processes. This information focuses on how research ensures the scientific community can replicate, validate, and build upon existing work [61]. By providing clear and precise descriptions of sampling, extraction, and processing techniques, researchers contribute to a cumulative consolidation of knowledge that enhances the reliability and efficiency of microalgae utilization. Integrating these emphases—practical applications, fundamental science, strategic impact, and methodological rigor—creates a well-rounded research field. This comprehensive approach accelerates technological innovation and deepens our scientific understanding, leading to more robust and versatile applications of microalgae across various domains. The interplay between applied research and foundational science thus ensures that advancements are grounded in solid theory and directed toward practical, real-world benefits.

3.2. Specific Applications

To better understand specific application trends, bibliometric analyses were performed on biofuel technology, biomolecule production, bioremediation, CO_2 fixation, and food technology. Table 9 details the number of documents retrieved from these analyses.

Table 9. Number of documents analyzed from specific applications' equations.

Database	Bioremediation	Industrial and Medical Interest Biomolecules	Biofuels	Food	Carbon Fixation
Scopus	1878	1715	2487	2651	1386
Web of Science (WoS)	17	11	53	36	8
Lens	62	62	135	150	70
Final Data [1]	1887	1724	2534	2543	1415

[1] Number of documents after unification and removal of duplicates.

Thematic maps of Title information allow for the comprehension of trends among specific applications. They consider clusters of terms and group themes that can be positioned by relevance and development degree (Figure 8). Particular focus was placed on the Basic Themes area, considering clusters represent transversal themes and opportunities to develop relevant knowledge [62].

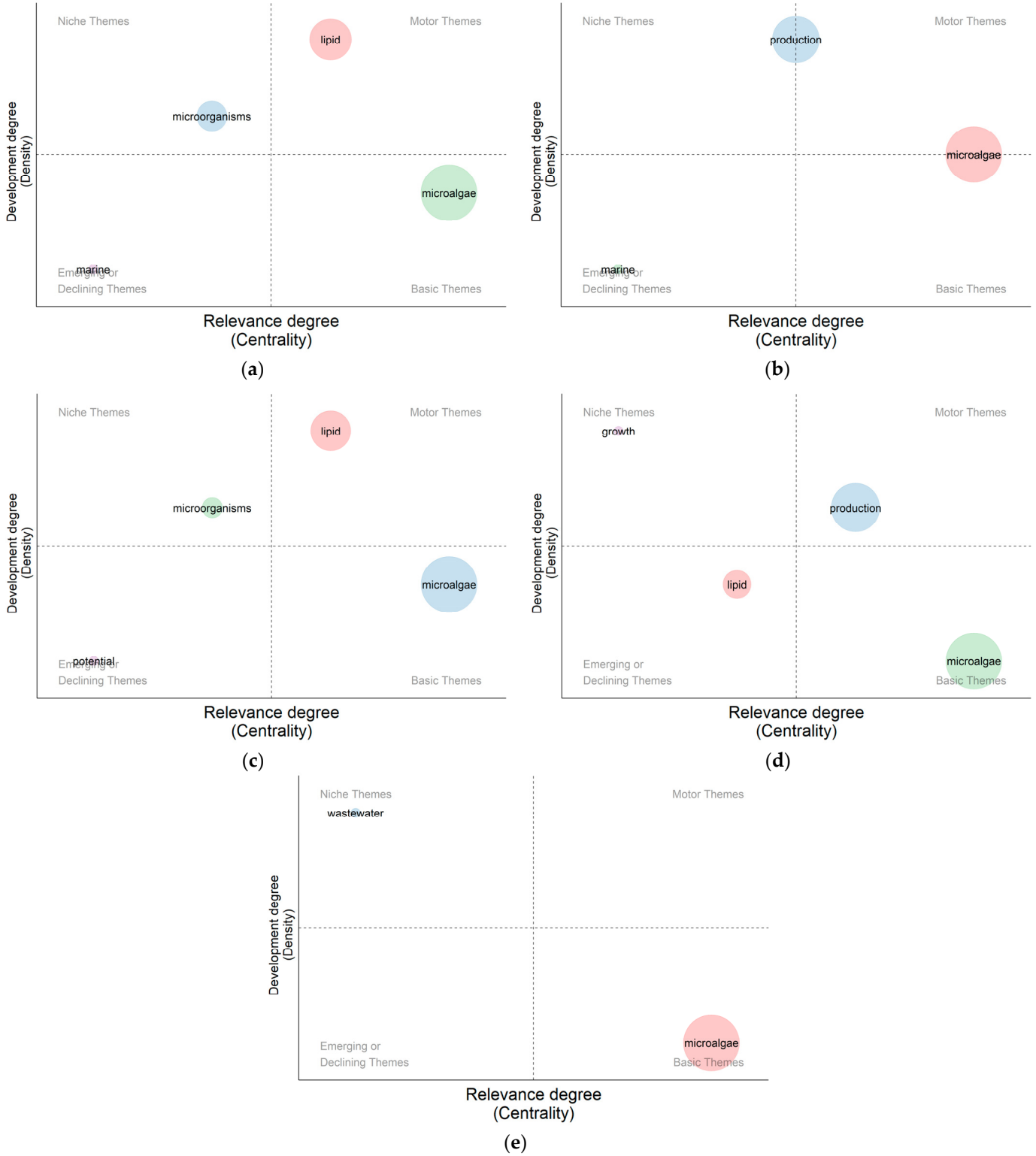


Figure 8. Thematic maps of the specific applications' equations: (**a**) bioremediation; (**b**) industrial and medical interest biomolecules; (**c**) biofuels; (**d**) food; (**e**) carbon fixation.

3.2.1. Bioremediation: Biomass Production for Multipurpose Technologies Trend

Bioremediation's map displays four clusters, with the Microalgae and Lipid clusters being particularly interesting due to their relevance. The Microalgae cluster demonstrated the highest Cluster Frequency with 4.585 and comprises terms related to production and biomass, wastewater treatment, combined strategies with biofuels and energy technology,

derived value-added products, processes, and sector application. On the other hand, the Lipid cluster, with a Cluster Frequency of 2.702, comprises terms associated with the production of lipid and fatty acids, cultivation and growth conditions, biochemical and metabolic studies, and optimizations and enhancement processes. Other clusters in this analysis show transversal interests that can be used to position future studies, but their terms should not be declared as protagonists (Table 10).

Table 10. Top 20 terms in the Bioremediation clusters.

Microalgae		Lipid		Microorganisms		Marine	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
microalgae	835	lipid	158	microorganisms	165	marine	88
production	529	cultivation	114	sustainable	148	applications	87
wastewater	250	growth	109	environment	74	application	56
biomass	226	chlorella spp	106	challenges	70	compounds	56
biofuel	177	nutrients	90	bioremediation	69	bacteria	50
potential	173	removal	80	perspective	69	biotechnological	46
biodiesel	137	acids	73	recent	69	bioactive	40
treatment	116	effects	76	future	59	fungi	37
industrial	74	strain	72	technology	57	biotechnology	35
source	75	fatty	64	current	51	natural	35
green	70	diatom	56	advances	46	extraction	29
bioprospecting	69	enhancement	50	approaches	43	synthesis	28
waste	66	isolated	48	resource	39	pigments	27
biorefinery	63	characterization	46	prospects	38	diversity	24
products	61	effluent	42	trends	36	exploring	23
process	48	vulgaris	43	remediation	33	health	22
approach	48	species	39	emerging	30	nanoparticles	19
energy	45	municipal	39	engineering	26	yeast	17
cyanobacteria	45	conditions	36	enzymes	26	functional	15
system	43	culture	36	heavy	26	seaweed	14

Given that the thematic map was generated from document titles related to bioremediation, this cluster offers insights into the prevailing research themes and emerging trends in this field. Research focuses on microalgae species used for bioremediation or, specifically, phycoremediation. Several titles comprise terms such as production, biomass, wastewater, and treatment, indicating a strong focus on biomass generation from these microorganisms for various applications, including bioremediation and a practical application of this biomass in treating industrial and municipal wastewater. Interestingly, concepts such as biofuel, biodiesel, bioethanol, energy, and bioenergy were also frequent, indicating an interest in combined technologies. Terms associated with environmental and economic benefits also constituted this cluster, suggesting an association between this biotechnology and its declaration across different application sectors. There is a strong emphasis on developing efficient processes and technologies, evaluating their economic viability, and exploring their applications across various industrial and environmental sectors. This multifaceted approach points out the potential of bioremediation not only as a solution for pollution but also as a contributor to sustainable energy and resource management [63–70].

3.2.2. Industrial and Medical Interest Biomolecules: Bioproduct Synthesis and Their Sustainable Production Trend

Analysis of Industrial and Medical Interest Biomolecules generated three clusters, of which Microalgae and Production clusters are of interest in this trend analysis. No clusters were in the Basic Themes area, but the Microalgae cluster is between it and Motor Themes. This position suggests a recent growing trend of developing knowledge in its terms. The Microalgae cluster comprises terms related to biological sources of bioproduct generation, lipids and fatty acid production, antioxidant and antimicrobial compounds, and several

applications such as nutraceuticals, therapeutic applications, nanotechnology, industrial and aquaculture. On the other hand, the Production cluster, which is between Motor and Niche Themes, presents terms with high relevance and a high degree of development, and they are constantly of interest. These terms comprise production and sustainability relationship concepts, commercial focus, challenges and perspectives, and integral impacts. Finally, the Marine cluster shows cross-interests that can be used to position future studies, but their terms should be considered as something other than the main themes (Table 11).

Table 11. Top 20 terms in the Industrial and Medical Interest Biomolecules clusters.

Microalgae		Production		Marine	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
microalgae	534	production	289	marine	219
lipid	111	microorganisms	178	potential	180
activity	98	sustainable	107	applications	127
acids	87	biomass	104	compounds	118
bioprospecting	90	products	90	bioactive	105
antioxidant	84	industrial	71	source	89
diatom	78	perspective	67	natural	86
fatty	74	wastewater	64	pigments	69
growth	58	biofuel	63	food	65
effects	57	future	61	biotechnological	58
cell	48	recent	57	metabolites	56
extraction	52	challenges	55	bacteria	54
green	53	cultivation	53	plant	51
application	53	current	54	fungi	48
carotenoids	49	environment	48	health	36
characterization	49	biotechnology	47	diversity	30
strain	48	advances	42	synthetic	24
cyanobacteria	46	biorefinery	42	functional	23
seaweed	45	engineering	41	therapeutic	23
isolated	39	development	39	discovery	22

There is an opportunity to develop innovations in biomedical and industrial applications of value-added products from microalgae because of their positioned clusters between thematic map areas. Specifically, bioprospecting microalgae for bioproduct synthesis and their sustainable production would be highly interesting in the present and near future [53,71–78]. Bioprospecting microalgae for pharmaceuticals and secondary metabolites is highly promising due to its ability to produce diverse bioactive compounds such as antioxidants, antimicrobials, and anti-inflammatories [79,80]. Microalgae like *Chlorella*, *Arthrospira*, *Dunaliella*, and *Haematococcus* offer valuable compounds like carotenoids, phycocyanin, dinotoxins, and novel metabolites [80]. Their rapid growth and adaptability make sustainable, large-scale production feasible. Advanced biotechnological tools can enhance yield and efficiency, making microalgae a key resource for developing new, eco-friendly medical treatments and health products. Microalgae hold significant industrial and medical potential, offering sustainable solutions for biomaterials, biodegradable plastics, and nutraceuticals due to their high lipid content and rich nutrient profile. They provide essential fatty acids, vitamins, and proteins for agricultural applications, dietary supplements, and functional foods, and their bioactive compounds are being researched for cancer therapy, cardiovascular health, and neuroprotection [36,81–83]. Nevertheless, although microalgae bioproducts have strong potential, their commercialization still needs improvement due to research funding challenges, small-scale operations, and policy implementation [84,85].

3.2.3. Biofuels: Microalgae Biorefinery for Combined Actions Trend

Interestingly, the Biofuels map shows similar patterns in its clusters with the Bioremediation map, which is congruent with suggestions made in the Bioremediation anal-

ysis for combined technologies. The Microalgae cluster in the Biofuels map (Cluster Frequency = 4.763) presents terms showing various biofuel types, including biodiesel and bioethanol. This cluster also comprises terms associated with technological and methodological advances in production, biomass, fermentation, co-product generation, and dual action with wastewater treatments. Conversely, the Lipid cluster highlights comprehensive and multidisciplinary terms for optimizing microalgae cultivation and biofuel production. The focus on lipid and fatty acid production, strain improvement, nutrient management, and environmental optimization indicates a robust effort to enhance the efficiency and yield of biofuels as a continuous field of knowledge development. Finally, the Microorganisms and Potential clusters add terms that could be strengths in future biofuel studies (Table 12).

Table 12. Top 20 terms in Biofuels clusters.

Microalgae		Lipid		Microorganisms		Potential	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
microalgae	1056	lipid	236	microorganisms	188	potential	236
production	674	acids	136	sustainable	173	marine	163
biomass	263	cultivation	129	industrial	97	applications	139
wastewater	251	growth	130	perspective	89	source	105
biofuel	223	chlorella spp	121	challenges	87	bioprospecting	101
biodiesel	173	fatty	116	future	86	compounds	86
treatment	117	strain	97	recent	79	bioactive	73
green	87	effects	98	products	75	application	68
waste	76	nutrients	96	technology	71	extraction	66
biorefinery	73	characterization	86	environment	70	cyanobacteria	66
analysis	59	diatom	81	current	65	food	65
cell	58	removal	77	bioremediation	60	biotechnological	59
plant	57	isolated	64	development	58	natural	55
approach	57	enhancement	63	advances	54	bacteria	51
process	55	activity	61	biotechnology	54	pigments	49
energy	54	antioxidant	56	engineering	51	metabolites	43
system	52	species	53	approaches	50	synthesis	39
feedstock	44	accumulation	47	fungi	48	diversity	37
metabolic	44	vulgaris	47	prospects	50	biological	34
stress	44	conditions	46	resource	44	seaweed	34

The research trends in biofuels from microalgae indicate a comprehensive and multidisciplinary approach [24,86–91]. Microalgae's central role, combined with a strong focus on sustainable production, wastewater treatment, and the biorefinery concept, highlights the potential of this area to contribute significantly to green energy solutions [37]. The focus around the turn of the century shifted to studies on the unsustainability of petroleum fuels and the exploration of alternative sources due to the limited capacity of biodiesel from oil crops, which introduced microalgae as a uniquely capable option [92,93]. This notable trend evolved to study microalgae's high photosynthetic efficiency and oil yield, noting the technical challenges and opportunities in biomass production, which are critical for commercial viability [94]. Technological advancements, economic viability, and co-product valorization drive the research forward. This dynamic field is poised to address critical environmental challenges while providing renewable energy and valuable byproducts. Now, the trend in biofuel production derived from microalgae is focused on combined actions with other biotechnology, but also in studying microalgae in biorefinery, which means that current trends are focused on metabolic processes that reach efficiencies for engineering.

3.2.4. Food: Functional Food and Bioactive Compounds Trend

For the Food search, the thematic map shows the formation of four clusters, from which clusters of Microalgae (Cluster Frequency = 4.972) and Production (Cluster Frequency = 3.949) are given special attention for the current analysis. The Microalgae cluster presents several

terms associated with the source (microalgal species and place), showing the diversity and bioactivity of microalgae for this purpose. On the other hand, the Production cluster group terms are associated with sustainability and previous analyses of a cluster named Production. Coincidently, the terms Biofuels and Bioremediation are observed in this cluster, which suggests a combined action, as was observed in the Biofuels and Bioremediation analyses. The terms in the Lipid and Growth clusters also show concepts that can be used to strengthen trend studies on food technology and microalgae (Table 13).

Table 13. Top 20 terms in Food clusters.

Microalgae		Production		Lipid		Growth	
Term	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**	**Term**	**Occurrence**
microalgae	882	production	561	lipid	179	growth	112
potential	253	biomass	230	acids	123	cultivation	98
microorganisms	229	wastewater	181	fatty	105	chlorella spp	92
marine	208	biofuel	165	activity	104	nutrients	70
applications	150	sustainable	159	antioxidant	91	enhancement	57
compounds	119	biodiesel	111	effects	91	removal	55
source	115	perspective	93	diatom	82	enhanced	44
bioactive	106	future	89	characterization	81	culture	41
bioprospecting	105	challenges	84	strain	76	conditions	41
products	100	treatment	84	isolated	61	assessment	39
natural	96	recent	82	carotenoids	59	vulgaris	39
industrial	93	current	71	evaluation	48	accumulation	32
food	83	environment	69	species	47	freshwater	32
pigments	79	biorefinery	68	composition	46	effluent	27
green	76	waste	66	optimization	40	anaerobic	27
extraction	72	technology	62	properties	40	nitrogen	26
cyanobacteria	71	advances	58	stress	40	productivity	25
cell	65	approach	53	chemical	39	native	24
application	68	bioremediation	52	screening	38	efficient	22
fungi	65	process	50	antimicrobial	33	light	22

The dominant cluster in food technology research with microalgae highlights a comprehensive exploration of their potential applications, particularly in health, nutrition, and industrial uses. The focus on bioactive compounds, biotechnological advancements, and sustainable production methods reflects a growing trend toward integrating microalgae into the food industry. This cluster emphasizes the importance of continued research and development to fully realize the commercial and health benefits of microalgae, positioning them as a valuable resource for the future of food technology [76,80,95–98]. The trends emphasize the role of microalgae in producing sustainable biofuels, treating wastewater, and contributing to a circular economy through biorefineries. Ongoing research addresses challenges and explores new opportunities to harness the full potential of microalgae, positioning them as a vital resource for sustainable food technology and environmental management.

3.2.5. Carbon Fixation: Emerging Opportunity to Promote Sustainability Trend

The last analysis based on the Carbon Fixation theme demonstrated a more exciting pattern compared to previous analyses due to the formation of only two clusters, with a clear dominance of the Microalgae cluster (Cluster Frequency = 4.589), which is in the Basic Themes area. This cluster comprises terms associated with production, multidisciplinary applications, and prospective concepts. By its side, the Wastewater cluster (Cluster Frequency = 2.660) includes terms related to biomass, cultivation, and strain characterization (Table 14). Interestingly, no direct concepts or low relationship of carbon fixation were found in both clusters, suggesting an absence of title declarations about this theme. This finding provides an opportunity to research microalgae and its focused application in

carbon fixation [99–102]. There is a strong need to develop this microalgal research field due to its incredible relevance and low degree of development.

Table 14. Top 20 terms in Carbon Fixation clusters.

Microalgae		Wastewater	
Term	**Occurrence**	**Term**	**Occurrence**
microalgae	625	wastewater	165
production	385	biomass	164
biofuel	153	lipid	104
microorganisms	117	biodiesel	101
potential	116	cultivation	85
sustainable	114	treatment	81
applications	85	growth	68
challenges	65	chlorella spp	62
marine	64	acids	58
perspective	62	nutrients	55
source	59	green	54
industrial	58	fatty	52
recent	58	removal	49
biorefinery	52	plant	40
future	50	effects	41
products	49	strain	39
waste	45	characterization	36
diatom	44	process	35
bioprospecting	42	system	36
technology	42	carbon	34

The biotechnological applications of microalgae have captured significant attention in scientific research, highlighting their potential in different fields, from biofuel production to environmental bioremediation. Different reviews have underscored the multifaceted uses of microalgae, focusing on their role as a raw material for high-value products, carbon sequestration, and wastewater treatment [31,37]. Critical reviews also further emphasize the importance of microalgae in sustainable energy solutions and the production of bioactive compounds [71,101]. Despite these advancements, a core trend in this study is the increasing focus on bioprospecting as a fundamental element in unlocking the full potential of microalgae biotechnology. This trend reflects the growing recognition that exploring and harnessing the diversity of bioactive molecules within microalgae is essential for advancing medical, industrial, and environmental applications. Thus, bioprospecting has become a cornerstone of current research, paving the way for discoveries and innovations in applied phycology.

Although microalgae are currently studied in terms of biomass production for several purposes, such as bioremediation and biofuel generation, microalgae biotechnology is still a promising multidisciplinary research field. Research in bioactive molecules for medical or industrial applications and carbon fixation or sequestration constitutes a call for researchers and R&D centers. Challenges, prospects, and opportunities are trending in several current review studies, meaning that applied phycology is growing.

4. Conclusions

The publication of research concerning microalgae exhibits an exponential growth trend, underscoring the burgeoning interest and research activities in this domain. The multidisciplinary nature of the publishing sources reveals a primarily applied focus in the studies of these microorganisms. Among the core sources identified, a minority specialize in phycology, while the rest span various fields, highlighting the wide-ranging applications and interest in microalgae research.

Countries leading in microalgae research often have well-defined technology transfer models and policies. This correlation suggests that clear technological frameworks and support mechanisms significantly contribute to advancements and leadership in this field.

The literature on microalgae research is dominated by terms such as "production" and "biomass", indicating a strong industrial focus. This emphasis on practical applications reflects the efforts to optimize the use of microalgae in various industries. The significant research in bioremediation and biofuels further highlights the practical relevance of microalgae. These areas are frequently studied together, accompanied by research into microalgae cultivation and biomass production. Additionally, there is notable interest in leveraging microalgae to generate high-value bioproducts and as a source of nutrition, highlighting the wide-ranging practical applications of microalgae and the relevance of any research.

While there are relatively few direct studies demonstrate the potential of microalgae for CO_2 capture, the photosynthetic nature of these microorganisms provides a compelling justification for ongoing research in this area. This potential for CO_2 capture not only features the environmental benefits of microalgae but also inspires future research direction, highlighting the exciting possibilities for microalgae to contribute to environmental sustainability.

The expansive and multidisciplinary research on microalgae reflects their versatile applications and significant industrial relevance. The leading countries in this research field benefit from robust technology transfer policies, and the focus on production and biomass draws attention to the practical and industrial motivations driving this research. While CO_2 capture remains underexplored, it represents a promising avenue for future studies, aligning with global sustainability goals.

To further enhance the impact of microalgae research, it is critical to recognize the growing importance of bioprospecting in this field. Exploring and identifying bioactive molecules within microalgae are increasingly recognized as key to unlocking new applications in medicine, industry, and environmental management. As the research community continues to delve into the diverse potential of microalgae, bioprospecting emerges as a fundamental approach that expands the scope of applied phycology and aligns with the global pursuit of innovative and sustainable biotechnological solutions. By integrating bioprospecting with existing research avenues, such as biomass production and bioremediation, the field of microalgae biotechnology is poised to make significant strides in addressing some of the most pressing challenges of our time. This holistic approach underscores the need for continued interdisciplinary collaboration and investment in research and development, ensuring that the full potential of microalgae is realized across various sectors.

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