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Artículo

Potential applications of microalgae bacteria consortia for waste treatment and valuable bioproducts

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Abstract: The application of microalgae and bacteria in wastewater treatment has attracted interest due to the greater environmental adaptability and stability resulting from their interactions, exceed those obtained with microalgae al sustainability and economic competitiveness. This manuscript aims to support existing and relevant literature on the use of microalgae and bacteria. As a result, numerous scholars and authors have been emphasizing recent research on the biotechnology of algae and bacteria, so this revision will be useful to advance and facilitate the technological development of biological processes.

Keywords: microalgae; bacteria; valuable bioproducts.

Posibles aplicaciones de los consorcios de bacterias de microalgas para el tratamiento de residuos y bioproductos valiosos

Resumen: La aplicación de microalgas y bacterias en el tratamiento de aguas residuales ha despertado interés debido a la mayor adaptabilidad y estabilidad ambiental resultante de sus interacciones, superando las obtenidas con microalgas a las de sostenibilidad y competitividad económica. Este manuscrito pretende apoyar la literatura existente y relevante sobre el uso de microalgas y bacterias. Como resultado, numerosos estudiosos y autores han hecho hincapié en las investigaciones recientes sobre la biotecnología de algas y bacterias, por lo que esta revisión será útil para avanzar y facilitar el desarrollo tecnológico de los procesos biológicos.
Palabras clave: microalgas; bacterias; bioproductos valiosos.

1. Introduction

Anthropogenic activities continue to produce a significant amount of wastewater discharge with society's rapid development. This wastewater typically contains organic pollutants, acids, alkalis, salts, nutrients, heavy metals, and other environmental contaminants that can degrade the environment (Mhedhbi et al., 2020). Physical processes such as filtration, adsorption, and reverse osmosis. Physical processes like filtration, adsorption, and reverse osmosis; chemical processes like coagulation, advanced oxidation, and ion-exchange; biological processes like activated sludge processes and microalgae-based methods; and hybrid processes are the conventional methods for treating wastewater. While chemical processes can result in secondary contamination, physical methods are energy-intensive and not cost-effective (Khan et al., 2023). Biological techniques, however, are environmentally and economically beneficial (Goh et al., 2023).

Through several studies, the use of bacteria and microalgae as essential elements in environmentally friendly biological techniques is becoming a growing trend. Through the processes of nitrification, adsorption, denitrification, anaerobic ammonia oxidation, and integration, bacteria eliminate pollutants. However, slow processes, ongoing maintenance requirements, limited applicability, and performance degradation due to abiotic conditions limit their use (Sátiro et al., 2022).

On the other hand, because of their high photon conversion efficiency, huge capacity for absorbing carbon dioxide (CO2), quick growth rates, and high productivity, microalgae are important biological resources with ecological significance. An eco-friendly method for the green remediation of the environment is offered by phycoremediation (Ishizaki et al., 2020).

Microalgae–bacteria consortia have been utilized for treating wastewater since the 1950s. Microalgae–bacteria consortia offer unique benefits for wastewater treatment, and an increasing amount of research has explored dual-species cultures of microalgae and bacteria for overall ecological improvement (Zhuang et al., 2023). Microalgae can offer a habitat that protects bacteria from unfavorable environmental conditions, increases bacterial growth rate, and lowers aeration requirements and energy costs; concurrently, bacteria not only promote the growth of microalgae and the productivity of their bioproducts but also increase the consortium's sedimentation rates, which lowers the costs associated with harvesting biomass (Lauritano et al., 2020). Furthermore, compared to the impacts of each component alone in wastewater treatment, microalgae–bacteria consortia can more successfully encourage the transformation of pollutants and enhance their environmental adaptability and stability (Ríos et al., 2023). It is economically feasible to treat environmental pollutants utilizing symbiotic microalgae–bacteria consortia because of these important benefits. One of the most important aspects of this technique, which has major implications for environmental management, is the interaction between microalgae and bacteria. Additionally, consortiums of bacteria and algae can create biofuels and other bioproducts.

Microalgae–bacteria consortia have great economic application potential in the circular bioeconomy as an efficient option for wastewater treatment and bioproduct manufacturing. Therefore, this article aims to provide a comprehensive overview of the microalgae-bacterial consortium interaction process. This review also focuses on providing a bibliometric analysis of the microalgae-bacterial consortium and showing the trend in the use of microalgae biotechnology. The study offered here is a significant contribution to bibliometric technique and can help improve understanding of the field of use of microalgae-bacterium consortium by offering recommendations to researchers.

2. Materials and Methods

2.1. Bibliometric Analysis

The terms "microalgae", "bacteria" and "wastewater" were used to search the title, abstract and keywords of the publication. The aim was to exclude products with a broad reach over microalgae and to give priority to those that focus on the use of consortia with batteries to obtain valuable products. A search was carried out between 2014 and 2023, with 936 documents retrieved from the Web of Science database (Clarivate). Bibliometric data were analyzed using the R bibliometric package and the open-source software RStudio (www.rstudio.com) (Silva *et al*., 2020). The VOSviewer software, available at www.vosviewer.com, was used to build and present the keyword co-occurrence network, as described by (Verasoundarapandian et al., 2022).

3. Results

3.1. Bibliometric analysis for microalgae harvesting with EC.

Microalgae are increasingly used by a variety of companies, so it is critical to investigate the trend of the use of microalga-bacteria consortium, Using the search terms "microalgae", "bacteria" and "wastewater", a methodical search was carried out in the Web of Science scientific database for this purpose. Data was collected from 936 publications, including research and review articles. The bibliometric characteristics, including the total number of cites, the average number of citations per article, the rankings of the most cited publications and the evolution of the subject of study were calculated using the Bibliometrix package of the R Commander software (x64 4.1.0). In addition, bibliometric maps were produced using co-occurrence analysis with VOSviewer. The Web of Science database was used to gather research data on microalgae-bacterial consortium use published between 2014 and 2023. Countries that had articles written on the subject were ranked (Figure 1), with China having the most cited (6560), which also has the most publications (1248) followed by the United States (1835). Consequently, the impact of these publications on the field and their potential value as references for future research are obvious. The information extracted from the database was classified according to the author's associated affiliation address. Reviews (131) and research articles (819) constitute most published papers.

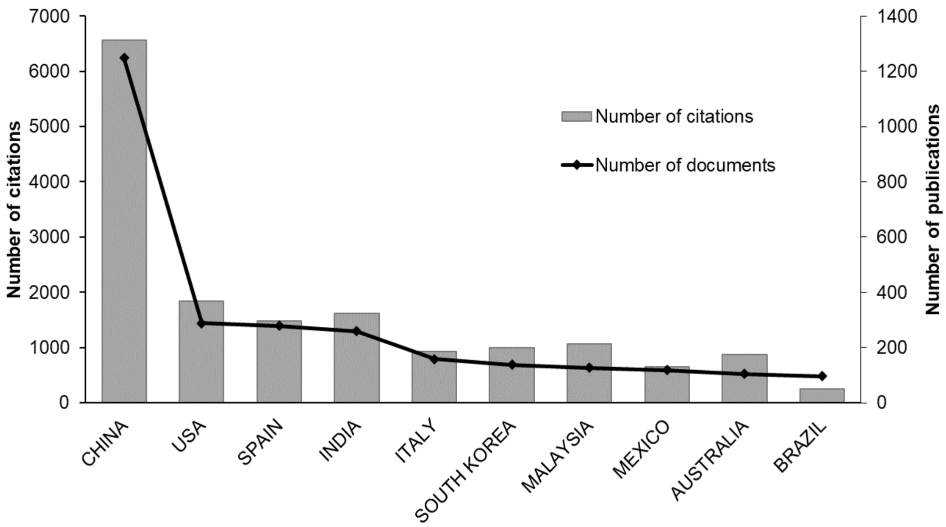

Figure 1. Key nations based on microalgae harvest data using microalga-bacteria consortium.

Table 1 presents a summary of the descriptive analysis performed on the data obtained from 2014 to 2023, utilizing the Web of Science database. 936 documents and 3122 authors were located during this search. Authors of single-authored documents were 7. The author/document relationship was 3.33 and the co-author/document ratio was 5.28.

Table 1. Descriptive analysis of retrieved data.

Description	
Documents	936
Period	2014-2023
Annual percentage growth rate	6.33
Average citations per documents	24.15
Authors	3122
Authors of single-authored documents	7
Documents per author	3.33
Coauthors per documents	5.28

Table 2 presents the most frequently cited papers pertaining to microalga-bacteria consortium. Notably, the papers pertinent to the review articles are categorized as significant reference papers. Additionally, the most influential contribution was made by the authors of the Portugal research institutions, who included 426 citations and 169.85 annual citations. To aid in the development and expansion of microalga-bacteria consortium, this review investigated the fundaments of this process.

Table 2. Works that have received the most quotations in worldwide studies on microalga-bacteria consortium.

Title	**Journals**	**Authors Affiliation Countries**	**Number of Citations**	**Number of Citations per Year**	**References**
A review on the use of microalgal consortia for wastewater treatment	Algal research-biomass biofuels and bioproducts	Portugal	426	60.85	(Gonçalves et al., 2016)
Interaction between Chlorella vulgaris and nitrifying-enriched activated sludge in the treatment of wastewater with low C/N ratio	Journal of cleaner production	USA	383	95.75	(Sepehri et al., 2020)
Perspectives on the feasibility of using microalgae for industrial wastewater treatment	Bioresource technology	Taiwan	281	35.12	(Wang et al., 2016)
Advanced nutrient removal from surface water by a consortium of attached microalgae and bacteria: A review	Bioresource technology	China	220	31.42	(Liu et al., 2017)
Use of hydrodynamic cavitation in (waste)water treatment	Ultrasonics sonochemistry	Slovenia	217	27.12	(Dular et al., 2016)
Removal of pharmaceutical and personal care products (PPCPs) from wastewater using microalgae: A review	Journal of hazardous materials	Australia	213	71	(Hena et al., 2021)
Effects of photoperiod on nutrient removal, biomass production, and algal-bacterial population dynamics in lab-scale photobioreactors treating municipal wastewater	Water research	South Korea	206	22.88	(Lee et al., 2015)
Trends and novel strategies for enhancing lipid accumulation and quality in microalgae	Renewable & sustainable energy reviews	South Africa	205	25.62	(Singh et al., 2016)
Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges	Biotechnology advances	South Africa	204	34	(Renuka et al., 2018)

Anaerobic digestate as substrate for microalgae culture: The role of ammonium concentration on the microalgae productivity enzymatic hydrolysis	Bioresource Technology	France	203	25.55	(Uggetti et al., 2014)

In addition, a thematic map was generated using Bibliometrix to illustrate the frequency of use of keywords in microalgae-bacteria consortium collection studies. (Table 2). The map, which considered references, authors, and the categories "microalgae" and "wastewater treatment" among others, revealed that these terms are most frequently used in China and Spain, respectively. An analysis of the research topics associated with this study's terms was done using keyword combination analysis. Figure 3 illustrates the results obtained. Keywords that appear at least twenty times are represented by a circle, with the diameter of each circle corresponding to the frequency of occurrence of the keyword. The keyword circle increases in size as it appears more often. The occurrence attribute of a keyword indicates the number of documents containing the key word. The clusters, marked by different colors on the map, function to distinguish sets of comparable elements. After a keyword that matches the network analysis, 936 were considered relevant and analyzed. As the results show, 11,529 link forces comprise 1212 links, while 52 elements are classified into five categories. The keywords (listed in Table 3) were used to generate five main categories, which correspond to the main fields of study associated with the collection of microalgae by the EC.

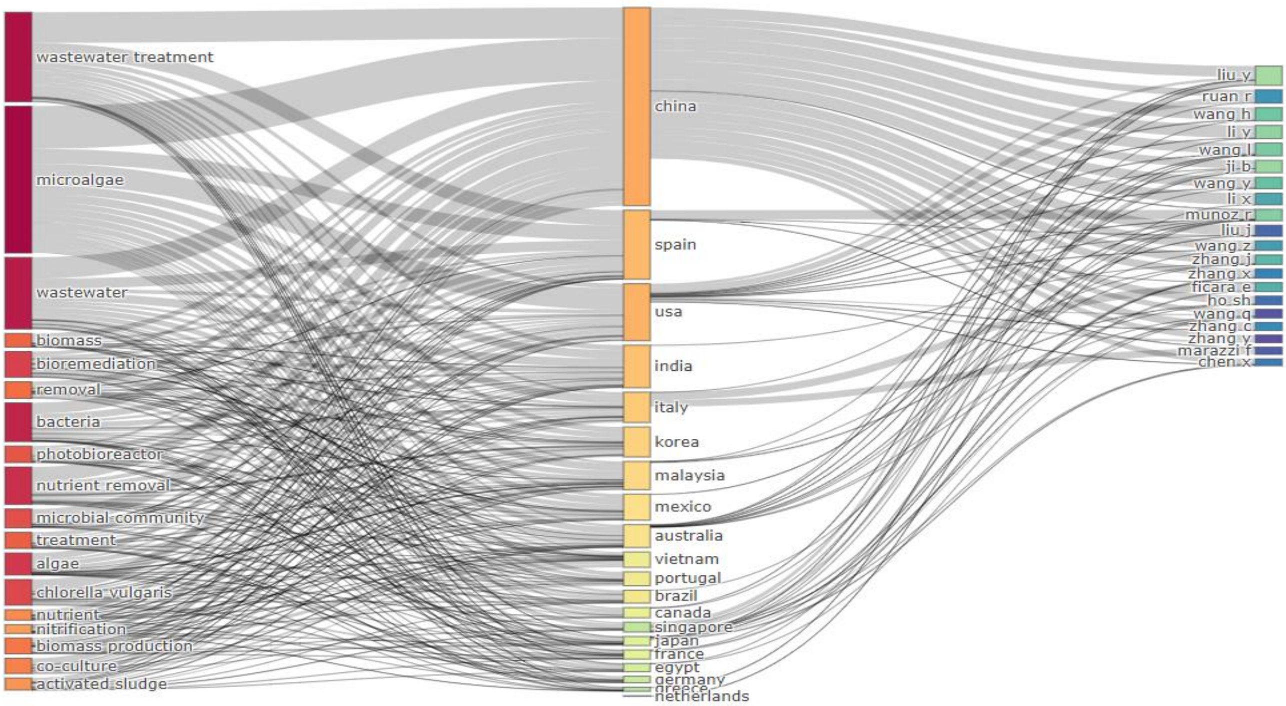

Figure 2. Thematic map of terms using microalgae bacteria (Bibliometrix).

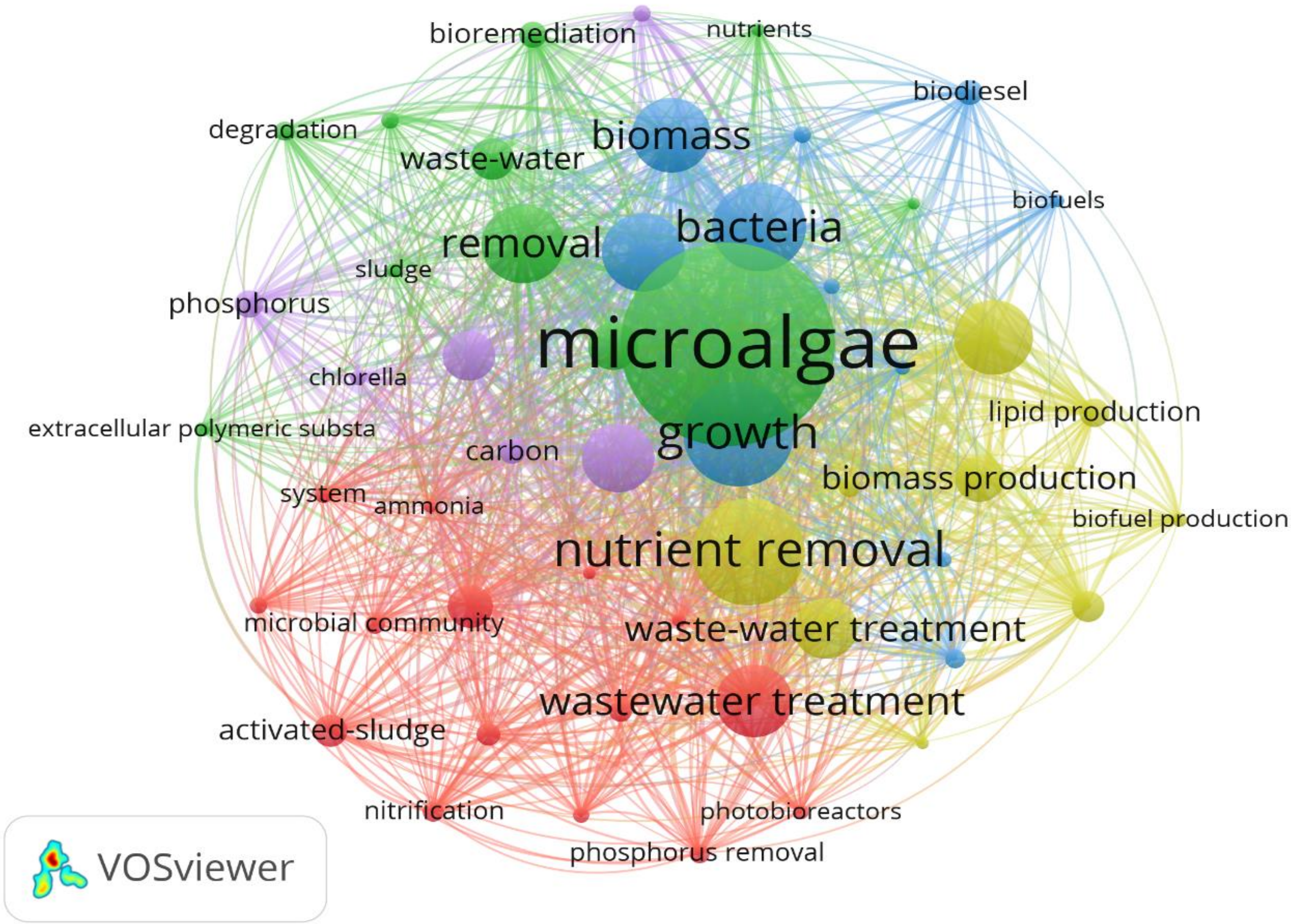

Figure 3. Keyword co-occurrence network analysis and emerging clusters (Cluster I: 15 words; Cluster II: 11 words; Cluster III: 11 words; Cluster IV: 9 words, Cluster V: 6 words).

Table 3. Words and clusters derived from co-occurrence network analysis of keywords.

Cluster	**Words**
Cluster I	15 words: activated-sludge, ammonia, consortium, culture, microbial community, nitrification, nitrogen removal, nutrients removal, performance, phosphorus removal, photobioreactor, photo-bioreactors, system, wastewater treatment and wastewaters.
Cluster II	11 words: biodegradation, bioremediation, cyanobacteria, degradation, extracellular polymerics substances, microalgae, nutrients, removal, sludge, wastewater and wastewater.
Cluster III	11 words: accumulation, bacteria, biodiesel, biofuels, biomass, chlorella vulgaris, cultivation, growth, light, recovery and temperature.
Cluster IV	9 words: Anaerobic-digestion, biodiesel production, biomass production, chlorella-vulgaris, light-intensity, lipid production, nutrient removal and waste-water treatment.
Cluster V	6 words: Algae, carbon, chlorella, effluent, nitrogen and phosphorus.

The main topics frequently found in scientific literature worldwide are illustrated in Figure 4. Most of the research topics concerned the use of microalgae and bacteria for water treatment.

Figure 4. Compilation of 52 topics shared in the academic papers on microalgae-bacteria.

The main journals are presented in Table 4. With 143, 68, and 47 articles, respectively, the main journals in which the authors studying microalgae-bacteria are Bioresource Technology (IF = 11.889), Algal Research-Biomass Biofuels and Bioproducts (IF = 5.276), and Journal of Science of the total environment (IF = 10.753)

Table 4. The main research journals on microalgae-bacteria, their impact factors, and the number of publications.

Journals	Impact Factor	Number of Publications
Bioresource technology	11.889	143
Algal research-biomass biofuels and bioproducts	5.276	68
Science of the total environment	10.753	47
Water research	7.481	39
Journal of water process engineering	7.34	32
Chemosphere	8.943	25
Journal of cleaner production	11.072	24
Journal of environmental management	3.644	24
Water science and technology	2.430	24
Environmental science and ecotechnology	11.357	22

3.2. Microalgae–bacteria consortia.

Wastewater presents a viable and economic growth medium for microalgae and bacteria due to its substantial nutrient content (e.g., carbon, nitrogen, phosphorus, and sulfur). Moreover, it enables the integration of microalgae cultivation and biorefining processes into the pre-existing wastewater treatment infrastructure (Microalgae, 2024). Multiple mechanisms, including bioadsorption, assimilation, biodegradation, bioaccumulation, biotransformation, nitrification, anaerobic ammonia oxidation, denitrification, and sulfur oxidation, enable microalgae–bacterium consortia to remove hazardous contaminants from diverse types of wastewaters (La Bella et al., 2022). The consortia of microalgae and bacteria exhibited greater stability and adaptability to complex environmental conditions than their constituent species. Utilizing microalgae–bacterium consortiums as a biological strategy for holistic ecological improvement has garnered considerable interest, specifically in the treatment of effluent from agricultural, industrial, and municipal origins.

3.3. Microalgae bacteria consortia for valuable bioproducts.

By comprehending the dynamic between microalgae and bacteria, it is possible to discern or form consortia of microalgae and bacteria that operate in a mutualistic manner, thereby optimizing the treatment of effluent resources and producing biomass simultaneously for biorefining objectives. Based on microalgae bacteria group technology, this closed-loop circular bioeconomy integrates clean water recovery, co-culture of microalgae bacteria, effluent resource treatment, biomass production, and derivative bioproduct generation. Microalgae bacteria consortia serve as an ideal feedstock for biorefineries, facilitating the generation of an extensive array of bio-products including but not limited to food, feed, biochemicals, biomaterials, high-value bioproducts, and diverse forms of bioenergy including biofuels, electricity, and heat (Gao et al., 2016).

4. Conclusions

This review offered a bibliometric analysis that contributed to the understanding of interactions involving microalgae bacteria consortia, with the goal of expanding their usefulness within the circular bioeconomy. The coexistence of bacterial species and microalgae is an inexorable consequence of evolution, giving them greater environmental stability and adaptability compared to their individual states. Recent research with an increase of 6.33% annually indicates that the microalgae bacteria consortia system presents considerable potential and benefits in the fields of effluent treatment and biorefineries in order to increase the likelihood that modern biotechnological implementations will succeed and advance in ecological development.

5. Conflicts of Interest

The authors declare no conflict of interest.

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