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Review Article

Bibliometrics of Microalgae and Cyanobacteria as Biofertilizers

Bibliometría de microalgas y cianobacterias como biofertilizantes

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Spanish version

Abstract

Introduction: Microalgae have emerged as a sustainable and effective option for agriculture, especially in their use as biofertilizers. Due to their adaptive properties and their capacity to efficiently absorb nutrients, they can be used to improve soil quality and promote plant growth.
Objective: To analyze indexed research on microalgae and their use as biofertilizers in agriculture.
Materials and Methods: A systematic search was initially conducted in the Scopus database, focused on articles related to the study topic. Subsequently, the Bibliometrix tool was applied for the bibliometric analysis.
Results: Two hundred relevant articles were identified, with India as the country with the highest production of publications in this field. The application of microalgae in wastewater treatment is also investigated, thereby promoting agricultural sustainability. Nitrogen-fixing cyanobacteria, such as Nostoc and Anabaena, improve soil fertility and reduce the need for synthetic fertilizers, while microalgae such as Chlorella vulgaris and Spirulina platensis improve productivity, stress resistance, and soil health.
Conclusions: Despite their potential, research on the use of microalgae as biofertilizers is still in early stages of development. There is an increasing scientific interest in their agricultural application, but further studies are required to consolidate their sustainable implementation at a productive scale.

Keywords: Agriculture, Biostimulants, Biofertilizers, Cyanobacteria, Microalgae.

Resumen

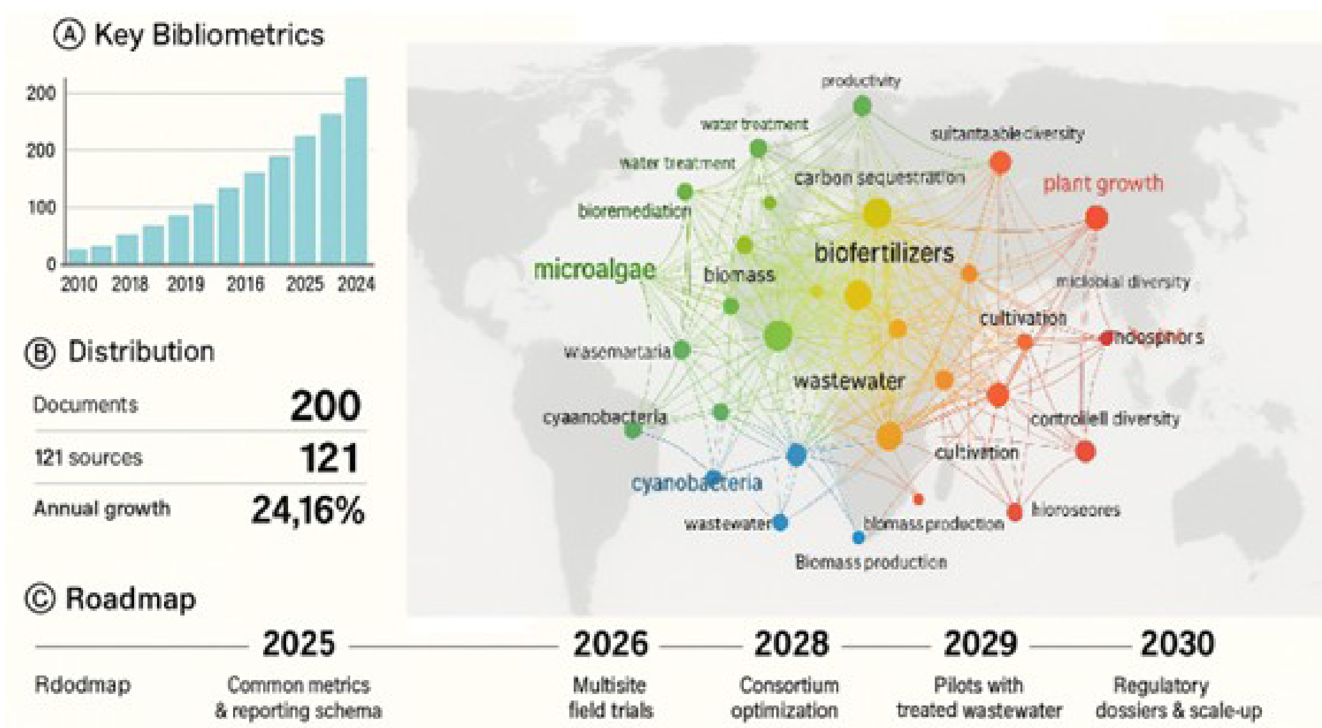
Introducción: las microalgas han emergido como una opción sostenible y eficaz para la agricultura, especialmente en su uso como biofertilizantes. Gracias a sus propiedades adaptativas y su capacidad para absorber nutrientes de manera eficiente, pueden ser aprovechadas para mejorar la calidad del suelo y promover el crecimiento de las plantas.
Objetivo: analizar las investigaciones indexadas sobre microalgas y su utilización como biofertilizantes en la agricultura.
Materiales y Métodos: se realizó inicialmente una búsqueda sistemática en la base de datos Scopus, focalizada en artículos relacionados con el tema de estudio. Posteriormente, se aplicó la herramienta Bibliometrix para el análisis bibliométrico.
Resultados: se identificaron 200 artículos relevantes, siendo India el país con mayor producción de publicaciones en este ámbito. También se investiga la aplicación de microalgas en el tratamiento de aguas residuales, promoviendo así la sostenibilidad agrícola. Las cianobacterias fijadoras de nitrógeno, como Nostoc y Anabaena, mejoran la fertilidad del suelo y reducen la necesidad de fertilizantes sintéticos, mientras que microalgas como Chlorella vulgaris y Spirulina platensis mejoran la productividad, la resistencia al estrés y la salud del suelo.
Conclusiones: a pesar de su potencial, las investigaciones sobre el uso de microalgas como biofertilizantes aún están en etapas tempranas de desarrollo. Se evidencia un creciente interés científico en su aplicación agrícola, pero se requiere profundizar en estudios para consolidar su implementación sostenible a escala productiva.

Palabras clave: Agricultura, Bioestimulantes, Biofertilizantes, Cianobacterias, Microalgas.

Why was this study conducted?
This study addresses the environmental costs of conventional fertilization and the lack of a focused, data-driven overview of microalgae and cyanobacteria as biofertilizers/biostimulants. We mapped the global research landscape in Scopus (2010–2024; data cutoff Jan 31, 2025) using Bibliometrix and VOSviewer (threshold ≥5 keyword occurrences) to quantify output, actors, venues, themes, and collaboration, and to identify trends, gaps, and opportunities aligned with sustainability and circular economy.

What were the most relevant findings?The review maps a fast-growing field: 200 documents (24.16% annual growth) from 121 sources, averaging 41.16 citations per paper, authored by 939 researchers (5.46 co-authors/paper) with 20.5% international collaboration. Output is led by India (followed by Spain, Brazil, Italy, Egypt, Morocco); Journal of Applied Phycology and Science of the Total Environment are most prolific. Five themes dominate: plant physiology/abiotic stress and bioactives; bioenergy/bioremediation/circular economy; biomass/cultivation/biochemistry; agri-biotech applications; and soil fertility/nutrient recycling/wastewater. Applications consistently benefit major crops via N-fixation (Nostoc, Anabaena), phytohormones, and polysaccharides, delivered as biomass, extracts, biochar, seed priming, or foliar sprays, with strong links to wastewater reuse and circular models. Key gaps include field validation, standardization, scale-up (TEA/LCA), and regulatory pathways, with limited Latin American output beyond Brazil.

What do these findings contribute?
A comprehensive, quantitative map of a fast-growing, multidisciplinary field clarifying who is publishing, where, on which crops/mechanisms, and with what tools and venues. Evidence that microalgae/cyanobacteria can enhance yields, stress tolerance, and soil health while enabling nutrient recovery and wastewater integration for circular models. Practical guidance: match species and delivery modes (e.g., Nostoc/Anabaena for N-fixation; Chlorella/Spirulina extracts for biostimulation) to crop targets and on-farm constraints. A research agenda: standardize protocols and reporting, expand field-scale trials, conduct TEA/LCA, develop regulatory roadmaps for engineered strains, and strengthen collaborations (notably in Latin America).



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Introduction

Agriculture plays an essential role in the economic growth of nations, being key to ensuring global food security. To increase agricultural production, modern practices and various types of fertilizers have been implemented on a large scale. However, the constant use of chemical fertilizers has led to significant ecological damage, including soil degradation, water pollution, loss of biodiversity, and posing risks to human and animal health (1). These problems are exacerbated by rapid global population growth, which requires a substantial increase in food production. In this context, conventional agricultural practices relying on synthetic fertilizers and pesticides are being challenged for their negative environmental impact. These methods affect long-term agrarian sustainability and threaten global food security. In the face of these challenges, a shift towards more sustainable agricultural practices that increase crop productivity and significantly reduce environmental damage is imperative (2).

Despite their enormous potential, several challenges limit the widespread adoption of microalgae-derived biofertilizers and biostimulants (3). High nutrient and water demands for large-scale cultivation represent economic and environmental barriers. In addition, the energy-intensive processes required for harvesting, extracting, and purifying bioactive compounds increase production costs (4). To overcome these obstacles, it is critical to adopt innovative approaches that improve microalgae production's sustainability and economic viability, such as circular economy models that integrate their cultivation with wastewater treatment. Interdisciplinary collaboration is essential to advance this field, bringing biological, chemical, engineering, and economic perspectives together to develop sustainable and wide-ranging solutions (5).

The use of chemical fertilizers in agriculture creates significant problems for soil health and the environment. In this context, biofertilizers and biostimulants derived from microalgae are positioned as sustainable alternatives to mitigate these adverse effects (6). Several studies have investigated the application of microalgae and cyanobacteria in agriculture, highlighting their role as biofertilizers and biostimulants in crops such as rice, corn, tomatoes, lettuce, onions, cucumbers, and other vegetables. In addition, their use in wastewater treatment has been evaluated, promoting more sustainable agriculture. Nitrogen fixation, particularly through cyanobacteria such as *Nostoc muscorum* and *Anabaena*, has improved soil fertility, reduced dependence on chemical fertilizers, and optimized crop growth (7). In bioremediation, microalgae and cyanobacteria have also been shown to be effective in recovering nutrients from wastewater, potentially generating valuable bioproducts such as biofuels and biofertilizers (8). Studies on the sustainability of these biofertilizers have shown their positive impact on nutrient recycling and improved soil health. Among the most widely used microalgae are *Chlorella vulgaris*, *Spirulina platensis*, *Scenedesmus* sp., and *Desmodesmus* sp., which are used in wastewater treatment and crop yield improvement. Rice, vegetable, corn, and wheat crops, as well as hydroponic systems, have been the subject of research demonstrating the benefits of microalgae in improving productivity, stress resistance, and soil quality (9).

Bibliometric analysis stands out as a fundamental tool for evaluating and understanding scientific knowledge, since it not only allows quantifying and visualizing academic production, but also identifying emerging trends and mapping collaborative networks. This approach integrates the

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measurement of the quantity and quality of publications, providing a comprehensive assessment of the impact on the advancement of science. In emerging areas, such as microalgae-based biofertilizers, its relevance is even greater due to the interdisciplinary nature of the field. The methodology facilitates the rapid detection of well-explored versus understudied areas, which is essential for guiding future research and defining scientific policies, while revealing synergies between disciplines such as agronomy, biotechnology, ecology and circular economy.

Methodology

Progress report on the use of microalgae as biofertilizers

For this study, an initial information search was conducted in the Scopus database (http://www.scopus.com; Elsevier B.V, Amsterdam, The Netherlands), focused on identifying publications on using microalgae as biofertilizers. Scopus offers advanced tools for citation analysis, co-authorship networks and impact assessment through multiple metrics, allowing for detailed and up-to-date bibliometric studies. Its ability to integrate quantitative and qualitative data facilitates the identification of emerging trends and thematic interrelationships between publications, key aspects for guiding future research and defining scientific policies. Scopus, recognized as one of the most comprehensive and up-to-date scientific platforms worldwide, provided access to cutting-edge data on microalgae applications in agriculture. This methodological approach facilitated the identification of recent advances and emerging trends in the field, providing a solid basis for assessing the potential of microalgae in improving agricultural processes.

Bibliometric analysis of the use of microalgae as a biofertilizer

A systematic search was conducted in the SCOPUS database, focusing on articles published internationally from 2010 to 2024, with data collection ending on January 31, 2025. The search strategy implemented included the terms TITLE-ABS-KEY (microalgae OR "micro-algae" OR cyanobacteria) AND (biofertilizer OR "natural fertilizer" OR bio-fertilizer OR bio-stimulant OR biostimulant) AND (agriculture OR agricultural OR horticulture) AND ("crop growth" OR "crop yield" OR productivity OR cultivation OR enhancement OR sustainability). VOSviewer software (version 1.6.19, Leiden University, The Netherlands) was used to assess keyword frequency for bibliometric analysis. A minimum threshold of five occurrences was set to ensure the results were representative and meaningful.

Each node in the analysis represents a keyword, with the size reflecting its frequency of occurrence, the color of its relationship and classification, and the links indicating the co-occurrence between terms. The information was then analyzed considering the following dimensions: 1) document production by year; 2) prominence of authors; 3) participating institutions; 4) relevant fields of study; and 5) geographic distribution of publications.

VOSviewer is an advanced tool for the construction and visualization of bibliometric maps. As described by Hamidah (10), this software allows visual representation of distributions of journals, authors, affiliations, and most cited articles, along with analysis of keyword frequency and relationships found using the search engine. In the present study, the combination of VOSviewer and Bibliometrix is essential in bibliometric analysis because of its ability to integrate

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intuitive visualizations and robust statistical analysis. VOSviewer excels in creating maps that reveal relationships in co-authorship, co-citations and co-occurrence of words, facilitating the identification of patterns, thematic clusters and emerging trends. In parallel, Bibliometrix, operating in the R environment, offers advanced tools to calculate key indexes and automate data extraction and cleaning, ensuring accurate quantitative analysis and reproducibility of results. Together, both tools enhance the rigor of the study by comprehensively addressing both qualitative and quantitative aspects, which is essential for guiding future research and academic policies.

An exhaustive analysis of the bibliography collected during the search focused on the most cited articles of the last 15 years. This literature review on using microalgae as biofertilizers highlights their significant potential to improve agricultural productivity sustainably. The results underline microalgae's growing importance in promoting greener and more efficient farming practices.

State of the art of microalgae as Biofertilizers in Colombia

Considering the limited availability of studies linking microalgae as biofertilizers, an exhaustive analysis of the state of the art on their application in agriculture was carried out. The main objective was to evaluate the potential of microalgae as a sustainable strategy to improve agricultural productivity and soil quality in the country.

Progress report on the use of microalgae as biofertilizers

Bibliometric analysis of the use of microalgae as a biofertilizer

Table 1 presents the relevant metrics on academic production and impact (2010-2024). The table summarizes quantitative data on sources and papers, highlighting elements such as the number of journals and books (121 sources), 200 papers, and an annual growth rate of 24.16%, suggesting a dynamic expansion in scientific production. The keywords section highlights two categories: amplified keywords (1485 terms) and author keywords (586 terms), providing a broad view of the thematic focus of the production. In terms of authorship, the image indicates 939 authors involved, with only five single-authored papers; in addition, international collaboration stands out, with 20.5% of co-authorships at the global level and an average of 5.46 co-authors per paper, which calls for a robust and collaborative research network.

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Table 1. Summary of Scientific Production Indicators

Period	2010:2024
Sources (magazines, books, etc.)	121
Documents	200
Annual growth rate (%)	24.16
Average number of citations per document	41.16
References	15480
Document content	
Keywords Plus (ID)	1485
Author keywords (DE)	586
AUTHORS	
Authors	939
Authors of single-authored documents	5
Collaboration of authors	
Co-authors per paper	5.46
International co-authorships	20.5

Figure 1 shows that during the first years (2010, 2012, and 2013), the indicator remained at zero, except for a slight increase recorded in 2011 with three articles. From 2014 onwards, the data show modest starts, with 1 article in both 2014 and 2015. Between 2016 and 2019, progressive growth was evident: 7 articles in 2016, 5 articles in 2017, 9 articles in 2018 and 10 articles in 2019. From 2020, the upward trend intensified significantly, reaching 15 articles in 2020, 24 articles in 2021, 30 in 2022, 45 in 2023, and culminating in 50 articles in 2024. The increase in publications is due to the convergence of a growing environmental awareness, which drives the search for sustainable alternatives to the impacts of chemical fertilizers, with technological and methodological advances that improved the cultivation and processing of microalgae, allowing their integration in diverse agricultural applications, and to greater financial and institutional support that, through policies of promotion and interdisciplinary collaboration, has boosted projects on the use of microalgae and cyanobacteria as biofertilizers.

The ascending line in annual scientific production from 2010 to 2024 suggests a growing interest and development in various research areas directly related to using microalgae in agriculture as bio inputs. It is plausible that this upward trend reflects the increase in research, publications, and technological projects exploring the potential of microalgae to improve soil quality and promote more sustainability.

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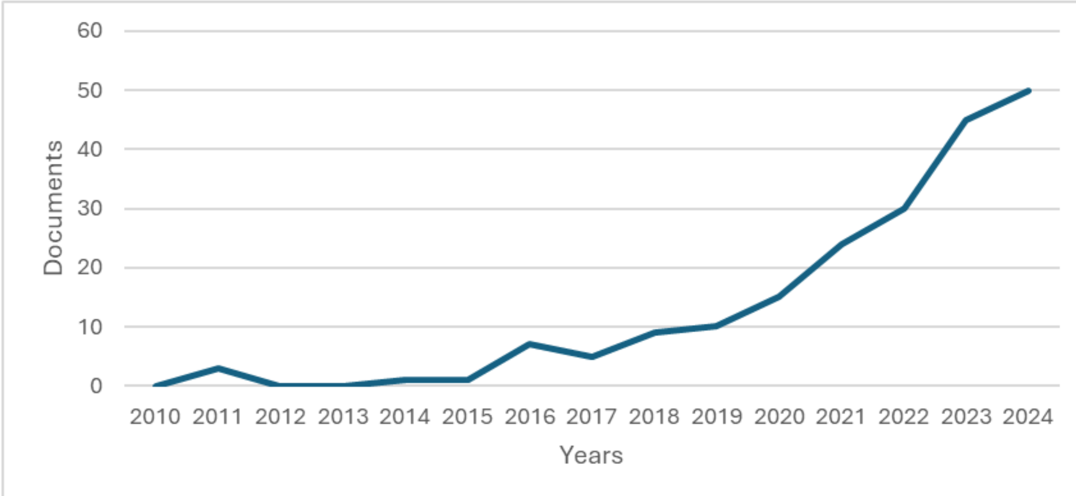

Figure 1. Evolution of the number of publications from 2010 to 2024

The different types of documents presented in Figure 2 classify 112 articles, two books, 30 book chapters, five communications in congresses, and 51 review articles, indicating diversity in the forms of dissemination of knowledge and a clear tendency towards publication in specialized journals, in addition to a strong component of systematic reviews. Review articles analyze previous studies on a topic, providing a structured overview of current knowledge in a quick and accessible way for both experts and beginners. As they do not require primary data, they are less costly to produce and facilitate the identification of advances and gaps, thus guiding future research and supporting scientific policies.

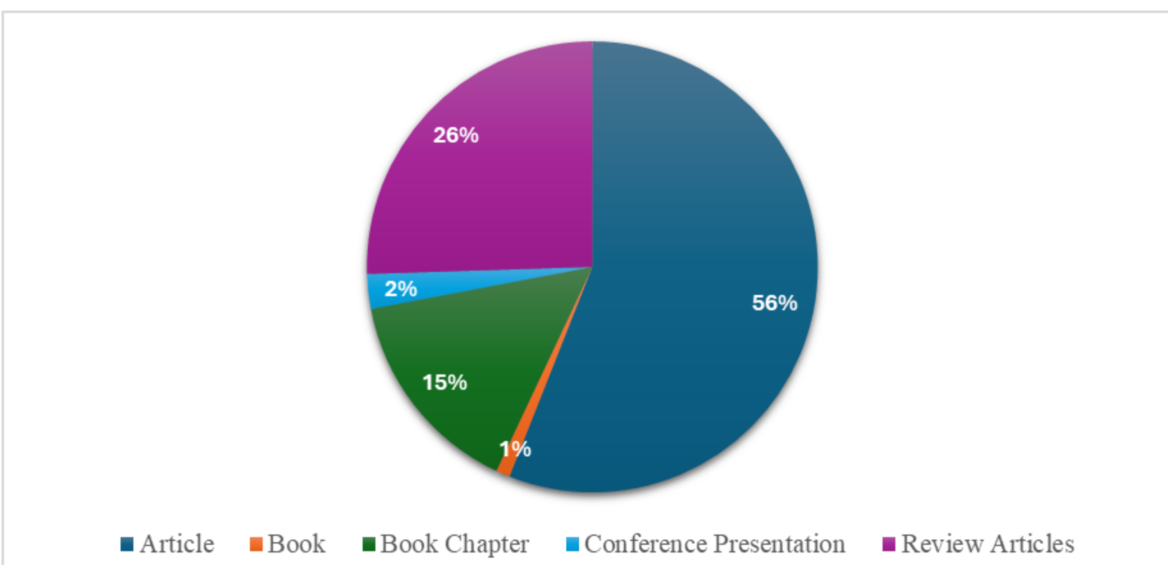

Figure 2. Distribution of different types of documents

Once the country of origin of each publication was identified, the RStudio bibliometrix package was used to classify them according to their production in the field of microalgae research applied as biofertilizers and biostimulants. In Figure 3A, India recorded the highest number of publications, consistent with the highest total citations. Spain, Brazil, Italy, Morocco, and Egypt follow it. Notably, Brazil is the only Latin American country to score highly in this analysis, indicating its position as a

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key player and leader in scientific research in the region, contributing significantly to the production and influence of Latin American research. Furthermore, the presence of several European countries in the top positions highlights the continent's strong tradition of research excellence, as they tend to lead in various scientific fields and foster cross-border collaboration, thus reinforcing their authority and impact.

Figure 3B presents a horizontal bar chart that differentiates publications assigned to a single country (SCP) from those from multi-country collaborations (MCP). Each bar is segmented into two colors, visually distinguishing between national and international research. This representation is evidence of India's remarkable research activity compared to other countries while highlighting domestic and global collaboration dynamics. In concrete terms, India, Spain, Brazil, Italy, Egypt, and Morocco lead in SCP publications, while India, Spain, Brazil, and Egypt lead MCP collaborations. Overall, this visualization facilitates a quick comparison of each country's performance in producing research papers, underlining the importance of cooperation in generating scientific knowledge.

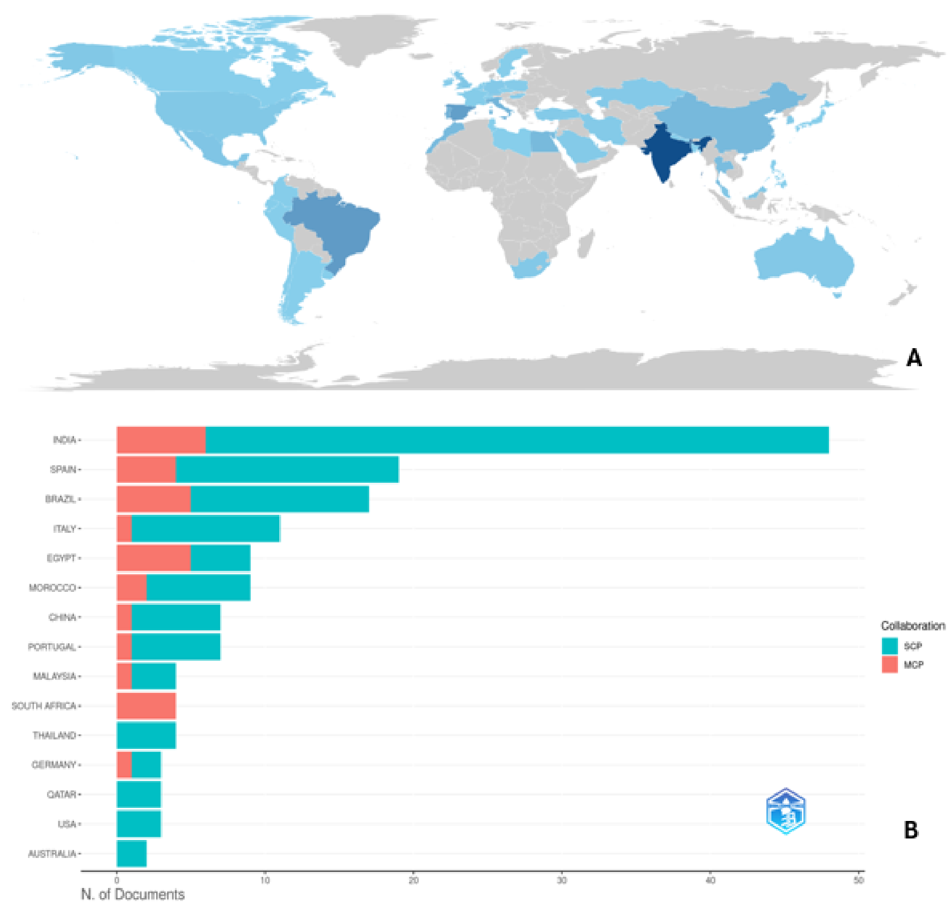

Figure 3. A. Most productive countries in microalgae are applied as biofertilizers and biostimulants. B. Production by country (SCP: single country publications, MCP: multi-country publications).

The frequency and association of terms present in the publications' abstracts, titles, and keywords were analyzed (Figure 4). This strategy made it possible to identify clusters of concepts that often appear together, suggesting a thematic or methodological relationship between the studies. The

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arrangement of the clusters also reflects the growing concern for environmental and economic aspects. Studies were grouped not only by biological mechanisms involving microalgae but also by their potential to contribute to sustainability, whether through bioenergy generation, climate change mitigation, or improved resource use efficiency in agricultural systems.

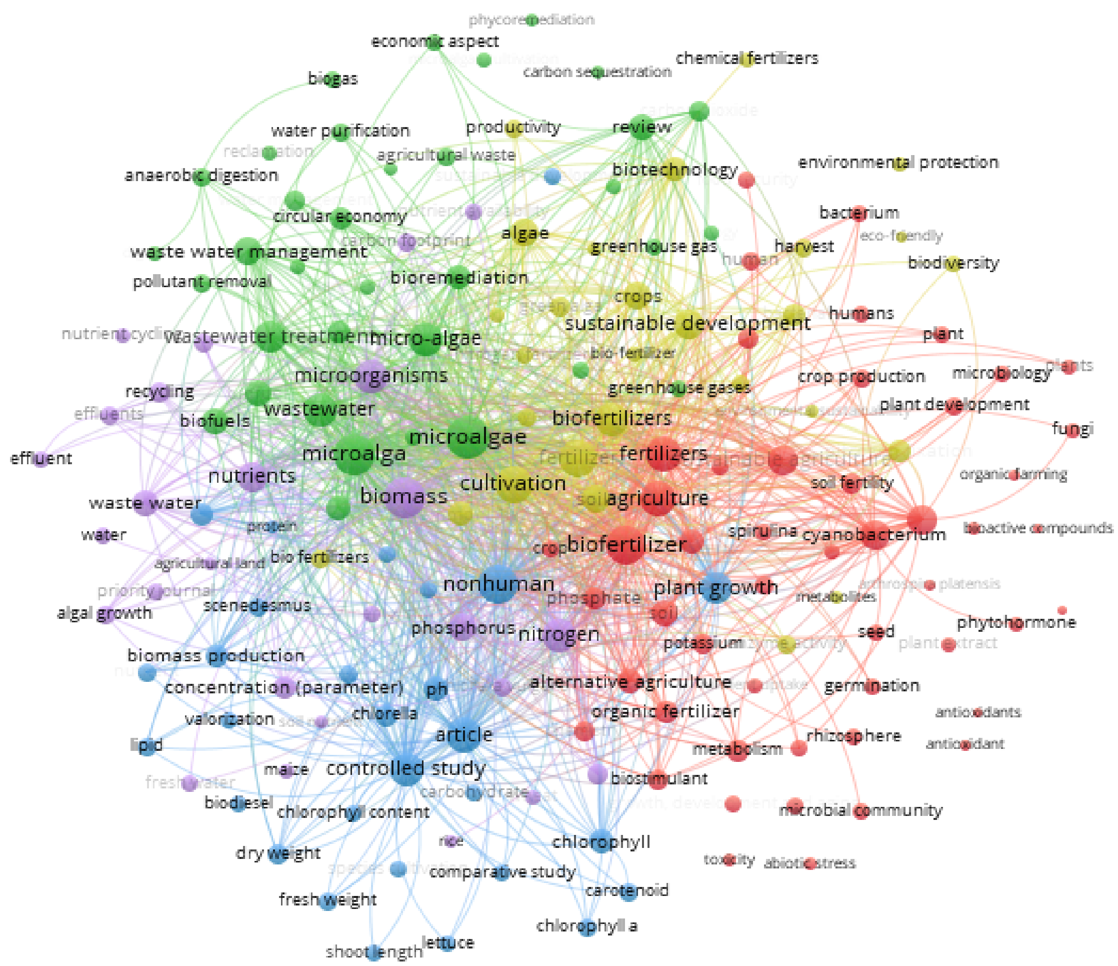

Figure 4. Bibliometric connections Microalgae as biofertilizers

Table 2 shows the 5 clusters established in the analysis. The first cluster (red) focuses on biochemical and physiological aspects (such as response to abiotic stress, effect of antioxidants, and growth regulators) related to improving crop yield and development. The second cluster (green) shows topics associated with converting biomass into bioenergy and biofuels, emphasizing anaerobic digestion techniques, bioremediation, and strategies for the circular economy. These aspects highlight the environmental and energy dimensions of the research. The third cluster (blue) is oriented to comparative biomass production studies, biochemical composition (pigments, proteins, lipids), and cultivation parameters, which allow for evaluating alternatives to conventional fertilizers. The fourth cluster (yellow) integrates research on technologies and processes that combine biotechnology with innovation in agriculture (e.g., agricultural robots and biofertilizers), focusing on productivity, environmental sustainability, and reducing the impact of chemical inputs. The fifth cluster (purple) addresses studies concentrating on practical applications, such as soil fertility improvement, nutrient recycling, and wastewater management, directly connecting

doi: 10.25100/iyc.v27i3.14884

to sustainable agriculture and resource management practices. In summary, Clusters 1, 4 and 5 form a logical chain of development: Cluster 1 lays the biochemical and physiological foundations for understanding the potential of microalgae and cyanobacteria; Cluster 4 uses this knowledge to generate technological and biotechnological innovations, facilitating the formulation and application of biofertilizers; and Cluster 5 translates these innovations into practical applications, improving soil fertility, promoting nutrient recycling and ensuring the sustainable management of agricultural resources.

Table 2. Microalgae Clusters as Biofertilizers

Cluster 1
abiotic stress, agriculture, alternative agriculture, antioxidant, antioxidants, *Anthrospira platensis*, bacterium, bioactive compounds, biofertilizer, biostimulant, chemistry, crop, crop production, crop yield, cyanobacteria, cyanobacterium, fertilizers, food security, Fungi, Germination, growth rate, growth, development, human, humans, iron, metabolism, microbial community, microbiology, mycorrhiza, nutrient uptake, organic farming, organic fertilizer, phosphate, phytohormone, plant, plant development, plant extract, plant extracts, plant leaf, plants, potassium, procedures, rhizosphere, seed, soil, soil fertility, spirulina, sustainability, sustainable agriculture, sustainable development, toxicity
Cluster 2
agricultural waste, algal biomass, anaerobic digestion, biofuel, biofuels, biogas, biorefinery, bioremediation, carbon dioxide, carbon sequestration, circular economy, climate change, digestate, ecology, economic aspect, gas Emissions, greenhouse gas, greenhouse gases, micro-algae, microalga, microalgae, microalgae cultivation, microalgal biomass, nutrient recovery, photobioreactor, phycoremediation, pollutant removal, reclamation, review, unclassified drug, wastewater management, wastewater, wastewater treatment, water management, water purification
Cluster 3
Article, biodiesel, biomass production, carbohydrate, carotenoid, chemical oxygen demand, C*hlorella*, chlorophyll, chlorophyll a, chlorophyll content, comparative study, controlled study, dry weight, electric conductivity, fresh weight, inorganic fertilizers, lettuce, lipid, microbial biomass, nonhuman, nutrient, ph, plant growth, protein, *Scenedesmus*, shoot length, specific cultivation, sustainable development, valorization
Cluster 4
agricultural robots, algae, ammonia, bacteria, bio-fertilizers, bio-fertilizer, biodiversity, biofertilizers, biotechnology, chemical fertilizers, crops, cultivation, eco-friendly, environmental impact, environmental protection, environmental sustainability, enzyme activity, fertilizer, green algae, harvest, metabolites, nitrogen fertilizers, nitrogen Fixation, photosynthesis, productivity, soils, sustainable development, water pollution
Cluster 5
agricultural land, algal growth, biomass, carbon, carbon footprint, *Chlorella vulgaris*, concentration (parameter), effluent, effluents, experimental study, fertilizer application, fresh water, maize, microorganisms, nitrogen, nutrient availability, nutrient cycling, nutrients, phosphorus, priority Journal, recycling, rice, soil nutrient, wastewater, water, wheat

Figure 5A (treemap) shows the predominant concepts in scientific publications related to using microalgae as biofertilizers and biostimulants. Of the total of 1485 entries collected covering both author-supplied and indexed keywords, 127 terms appeared with a frequency of at least five occurrences. The terms with the highest occurrence are highlighted below: 'biomass' (n=123), followed by 'microalgae' (n=86), 'microalgae' (n=61), 'agriculture' (n=58), 'cultivation' (n=52), 'fertilizers' (n=45), 'nitrogen' (n=44), 'cyanobacterium' (n=43), 'fertilizer' (n=43) and 'wastewater' (n=42). This word cloud-like visualization (Figure 5B) facilitates the rapid identification of the predominant themes in the study area, allowing us to understand the focus and interests of the research. It also highlights the interrelationship between these concepts, framed in the context

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of sustainability and optimization of agricultural processes through innovative microalgae-based solutions.

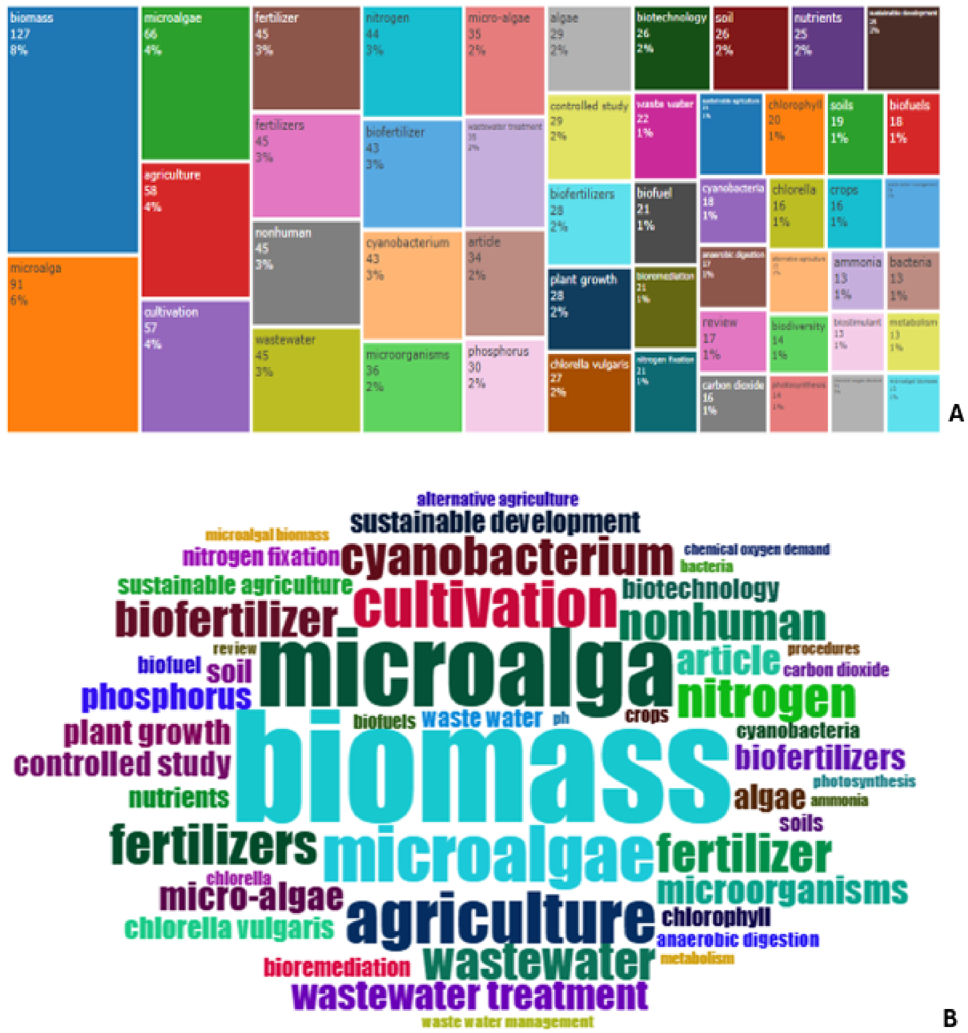

Figure 5. Keyword Analysis of Microalgae Use in Biofertilizers and Biostimulants: 5A Treemap and 5B Word Cloud Visualization

Table 3 shows information on the most relevant academic publications on using microalgae as biofertilizers or biostimulants, highlighting the most cited. Fields such as author(s), title, year of publication, DOI, and number of citations are included, which allows the identification of research trends and the impact of each study; there is evidence of a growing interest in the subject between 2016 and 2018, highlighting the importance of these studies for the understanding and improvement of agricultural productivity through sustainable practices.

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Tabla 3. Most relevant authors

Title	Year	Number of citations	DOI	Author
Biofertilizer and biostimulant properties of the microalga *Acutodesmus dimorphus*	2016	299	10.1007/s10811-015-0625-2	(11)
The use of microalgae as a high-value organic slow-release fertilizer results in tomatoes with increased carotenoid and sugar levels	2016	254	10.1007/s10811-015-0775-2	(12)
Microalgae as Bio-fertilizers for Rice Growth and Seed Yield Productivity	2018	172	10.1007/s12649-017-9873-5	(13)
Exploring the efficacy of wastewater-grown microalgal biomass as a biofertilizer for wheat	2016	169	10.1007/s11356-015-5884-6	(14)
Dunaliella salina exopolysaccharides: a promising biostimulant for salt stress tolerance in tomato (*Solanum lycopersicum*)	2018	151	10.1007/s10811-017-1382-1	(15)

Figure 6 presents a bar chart illustrating the performance of various universities and research institutes, evaluated in terms of their publications. This graph highlights the ten leading institutions with more than 183 publications. Of these, three are from Indian institutions, two from Spain, and one from Thailand, South Africa, Qatar, Morocco and Egypt. The aspects analyzed include the number of annual publications, the distribution of publications by institution and country, and the analysis of sources and keywords. This visual representation facilitates the identification of the main academic and research entities, allowing a quick comparison of their contributions to the field.

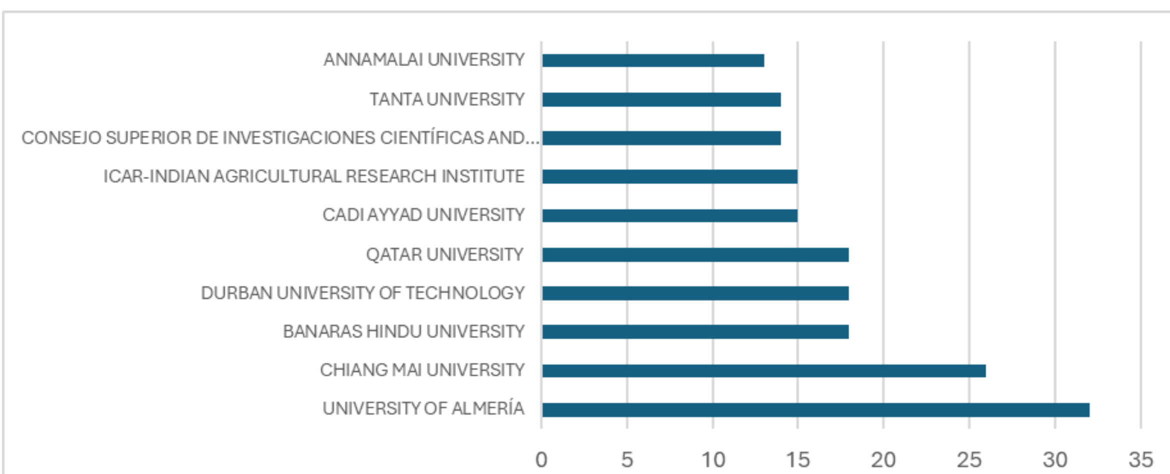

Figure 6. Leading institutions by number of scientific publications on microalgae as biofertilizer or biostimulant

Figure 7 presents the most publications in the top 10 journals and research fields. Among the journals evaluated, the Journal of Applied Phycology and Science of the Total Environment stands out for having 13 and 11 publications, respectively, which suggests that they have a high impact and relevance in the topic addressed. In an intermediate range are Bioresource *Technology* (7 publications), *Algal Research* (6 publications), *Agronomy* (5 publications), *Journal of Environmental Management* (5 publications) and *Plants* (4 publications). In addition, journals such as *Biomass*

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Conversion and Biorefinery (3 publications), *Biotechnology Advances* (3 publications), and *Frontiers in Plant Science* (3 publications) occupy intermediate positions, which shows the diversity in performance and relevance of these sources within the field of study.

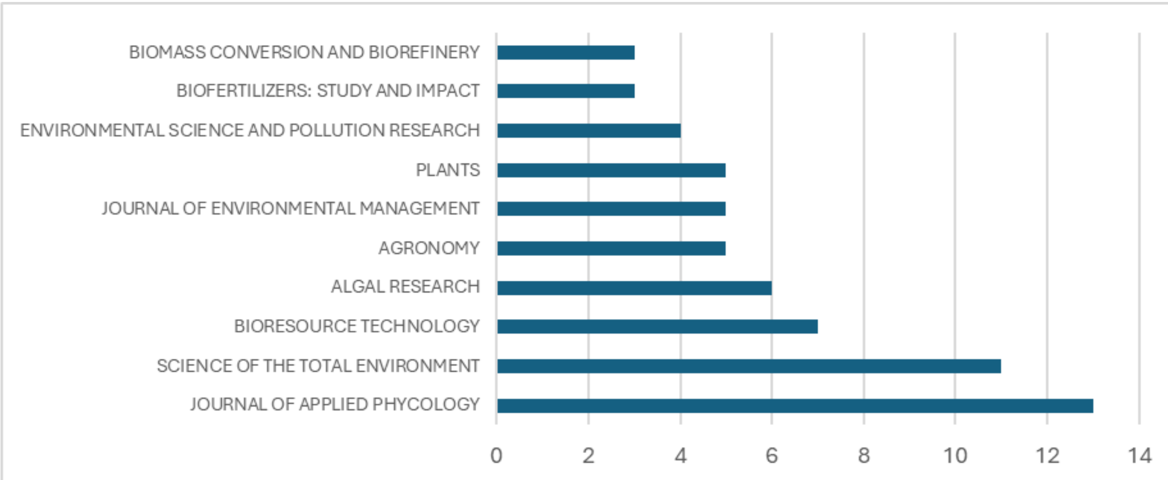

Figure 7. Journals with the Highest Scientific Output

There are a total of 21 study areas that track the development of research on microalgae and cyanobacteria as biofertilizers and biostimulants from 2010 to 2024, highlighting a multidisciplinary evolution aimed at improving agricultural productivity, environmental sustainability, and valorization of by-products. This integrated approach is reflected in the diversity of thematic areas represented in Figure 8, where "*Agricultural and biological sciences*" (26.5%) and "*Environmental sciences*" (21.5%) are the most prominent. These predominant categories underline the strong interest in practical applications in agriculture and environmental management. At the same time, other disciplines such as "*Energy*," "*Biochemistry, Genetics and Molecular Biology*," "*Chemical Engineering*" and "*Engineering*" contribute from complementary technical and molecular perspectives, showing how research has been enriched by interdisciplinary approaches to address problems of biofertilization, biostimulation, wastewater treatment, and phytoremediation.

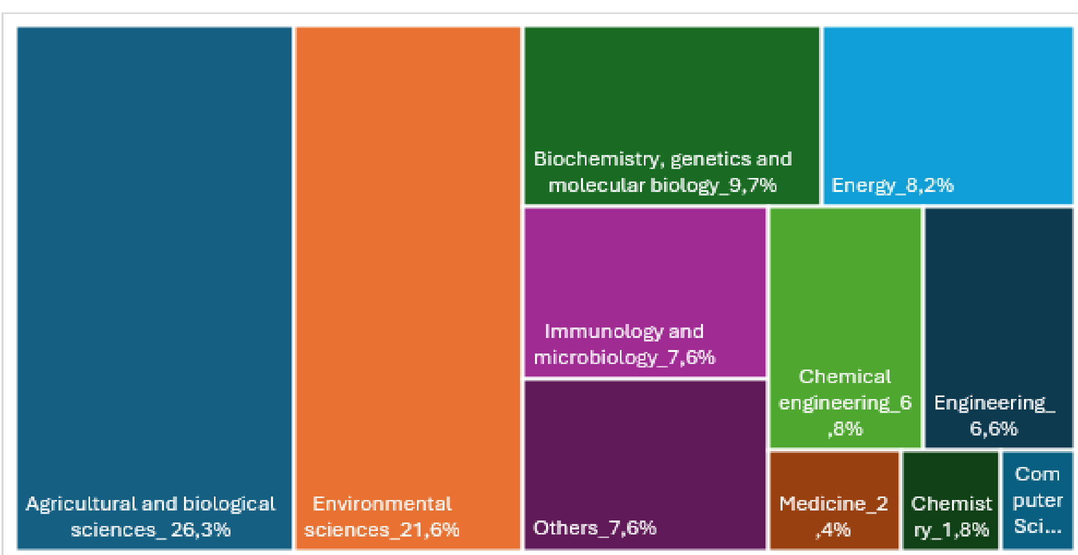

Figure 8. Documents by study area

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Literature review of the use of microalgae as biofertilizers

Microalgae and cyanobacteria, photosynthetic microorganisms with remarkable metabolic versatility, have emerged as promising options to address this critical need. Their ability to act as effective biofertilizers and biostimulants, offering a natural and environmentally friendly alternative to synthetic inputs, is the central focus of this review. Microalgae and cyanobacteria encompass many photosynthetic organisms that inhabit aquatic and terrestrial environments. Cyanobacteria, or blue-green algae, are prokaryotic organisms, while microalgae are eukaryotic, resulting in a biological diversity that generates a wide range of metabolic capabilities and bioactive compounds. This diversity makes them ideal candidates for sustainable agricultural applications, as their photosynthetic efficiency and ability to utilize diverse nutrient sources make them attractive for improving soil fertility and crop productivity (16). Well documented examples of microalgae, such as *Chlorella vulgaris*, *Spirulina platensis*, *Acutodesmus dimorphus*, and *Scenedesmus* sp., have significantly benefited agriculture (17). In addition, cyanobacteria such as *Anabaena* and *Nostoc* are known for their ability to fix nitrogen, improving soil fertility (18).

The beneficial effects of microalgae and cyanobacteria on crop growth are due to the bioactive compounds they produce, which act through various mechanisms, influencing key aspects of plant physiology. Phytohormones, such as auxins, cytokinins, gibberellins, and abscisic acid, regulate plant growth and development. Microalgae produce these hormones, favoring stem elongation, flowering, and fruit formation (19). In addition, the polysaccharides generated by these microalgae improve soil structure, water retention, and nutrient availability. Micronutrients such as iron, zinc, and manganese contribute to overall plant well-being, while enzymes such as phosphatases and potassium solubilizers increase nutrient availability in the soil (3).

Some species also produce compounds that activate plant defense mechanisms, improving their resistance to biotic and abiotic stresses. The application of microalgae and cyanobacteria in agriculture is highly versatile. Various application techniques have been explored, each with advantages and disadvantages. For example, seed preparation by soaking in microalgae extracts before planting improves germination rates and seedling vigor. Foliar sprays provide rapid bioactive compound delivery to plants, enhancing photosynthetic efficiency and addressing nutritional deficiencies (20). Soil amendments, meanwhile, incorporate biomass or extracts from microalgae, providing a long-lasting source of nutrients and improving soil health and beneficial microbial activity. In tomato cultivation, several species have shown considerable promise. For instance, *Ulothrix klebsormidium* improved leaf length and biomass, as well as nitrogen and phosphorus content when applied as dry biomass (21), while *Acutodesmus dimorphus* increased flower buds and shoot length when used both as liquid extract and dry biomass (11). Additionally, *Asterarcys quadricellulare*, via foliar sprays, stimulated leaf area and fruit production, increasing sugar and amino acid contents (22). Also, polysaccharide crude extract obtained from *A. platensis*, *D. salina*, and *Porphyridium* sp. have shown an increased plant growth increases the number of nodes, carotenoids, chlorophyll, proteins, and nitrate reductase (23). In cereal crops like wheat, barley, rice, and corn, the responses were equally significant. *D. salina* enhanced wheat germination, shoot length, and salt tolerance (24), and combinations such as *Chlorella*, *Scenedesmus, Tetraselmis*, and *Nannochloropsis* sp., increased plant height and leaf number (14).

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C. vulgaris in combination with *Microcystis* sp., improved phosphorus availability in the soil (25), and *Anabaena cylindrica* boosted chlorophyll and nitrogen content in wheat's aerial parts (26). In barley, *A. platensis* increased ear length, grain yield, and harvest index (27) For rice, applications of *C. vulgaris* and *A. platensis* (13), *Scenedesmus dimorphus* (28), and a three-species mix of *Chlamydomonas*, *Chlorella*, and *Desmodesmus* sp., (29) consistently improved shoot and root length, dry weight, nutrient uptake, and seed count. *A. platensis*, applied as biochar, increased seed weight and grain area in rice (30). *Scenedesmus* sp., alone enhanced soil NPK availability (31), and a *Chlorella/Scenedesmus* mix boosted germination in wheat and watercress (32). Even *Tetradesmus obliquus* significantly increased wheat germination and tillering (33). Corn also responded well to *C. vulgaris* and *A. platensis* through enhanced germination, yield, and shoot growth (34), while a mix including *Neochloris conjuncta* and *Botryococcus braunii* increased plant dry weight using effluent liquid (35). A microalgae consortium further improved corn's shoot dry weight (36), and *Kappaphycus alvarezii* enhanced pigment production, fresh biomass, and metabolite levels (37). These data affirm that cereals benefit not only from increased growth but also from enhanced physiological traits and nutrient use when treated with microalgae in various forms. Leafy vegetables, legumes, and specialty crops also displayed significant improvements. *C. vulgaris* and *C. pyrenoidosa* improved germination and salinity tolerance in lettuce, rice, eggplant, and cucumber (38), while *A. platensis* enhanced seedling growth and increased polyamine levels in lettuce (39). In beets, liquid extracts of *C. vulgaris* and *S. cuadricauda* activates genes and root traits, improving nutrient acquisition and promoting significant plant growth (40). Applications of *C. vulgaris* improved dry weight and root length (41), and in combination with *S. obliquus*, improved both fresh matter yield and germination (42). A triad of *C. vulgaris*, *S. obliquus*, and *Haematococcus pluvialis* led to increases in height, root length, biomass, and antioxidant content in lettuce (43). In celery and lettuce, a mix of *Anabaena oryzae*, *Nostoc muscorum*, and *A. platensis* improved height, root development, and nutrient content (44). In beans, *Chlorella* sp., *C. vulgaris*, *Nannochloropsis salina*, and *A. platensis* enhanced growth, yield, and antioxidant capacity (45), while *C. vulgaris* alone increased height, biomass, seed count, and nodulation (46). For cucumber, *S. cuadricauda* and *Anabaena circinalis* increased height, stem diameter, and bud formation (47). In onion, *C. vulgaris* and *A. platensis* improved nitrogen levels and amino acid content (48), and *S. subspicatus* increased bulb quality and dry mass (49). Additional effects were noted in basil, where *C. vulgaris* increased leaf area and nutrient uptake (50); in spinach and baby corn, where *C. minutissima* promoted growth and soil fertility (51); and in quinoa, where *C. pyrenoidosa* improved all major vegetative parameters and soil NPK content (52). In strawberry, *C. fusca* elevated chlorophyll content per leaf area (53), and in lettuce, tomato, and cucumber, *Euglena gracilis* improved seedling vigor and root formation (54). *Chorococcum* sp., applied to beans, tomato, cucumber, and bell pepper, improved root length and count (55), while in ryegrass, *Chlorella* and *Scenedesmus* sp., improved shoot and root biomass and increased rhizospheric microbial diversity (56). Altogether, these studies confirm that the incorporation of microalgae and cyanobacteria in the form of dry biomass, liquid extracts, nanoencapsulations, and foliar sprays generally is found to exert positive effects on crop growth performance. In cereals, vegetables, legumes, and specialty crops, these organisms improve growth-related characteristics including height, biomass, and chlorophyll levels as well as physiological and biochemical traits such as antioxidant status, nutrient accumulation, and taste. Evidence is compelling for the use of microalgae and cyanobacteria

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as sustainable and all-purpose biostimulants to decrease synthetic fertilization and to improve both productivity and quality in a range of agricultural systems. The Sankey diagram (figure 9) summarizes the main types of crops, divisions of microalgae or cyanobacteria and their main effects.

Microalgal consortia are dynamic communities characterized by symbiotic interactions, both cooperative and competitive, that enhance their metabolic, biochemical and ecological capabilities (57). In these consortia, some species maximize photosynthesis and CO_2 fixation, while others contribute secondary metabolites (such as antioxidants, polyphenols and amino acids) that protect the whole against oxidative stress and pathogens (58). Nutrient exchange is fundamental, as certain strains release organic substances that act as a substrate or signal, stimulating the growth and activity of other microalgae, which favors the stability and efficiency of the system (59). In addition, interspecies communication, mediated by signaling molecules in a mechanism similar to quorum sensing, regulates cell density and coordinates adaptive responses to adverse conditions, even inducing the production of defensive compounds in some species (60). The resulting synergy and metabolic diversity exceed the sum of individual capacities, providing greater photosynthetic efficiency, resilience to environmental changes and tolerance to stressors, although competitive relationships are maintained that avoid the monopolization of resources and promote the heterogeneity of the consortium (61).

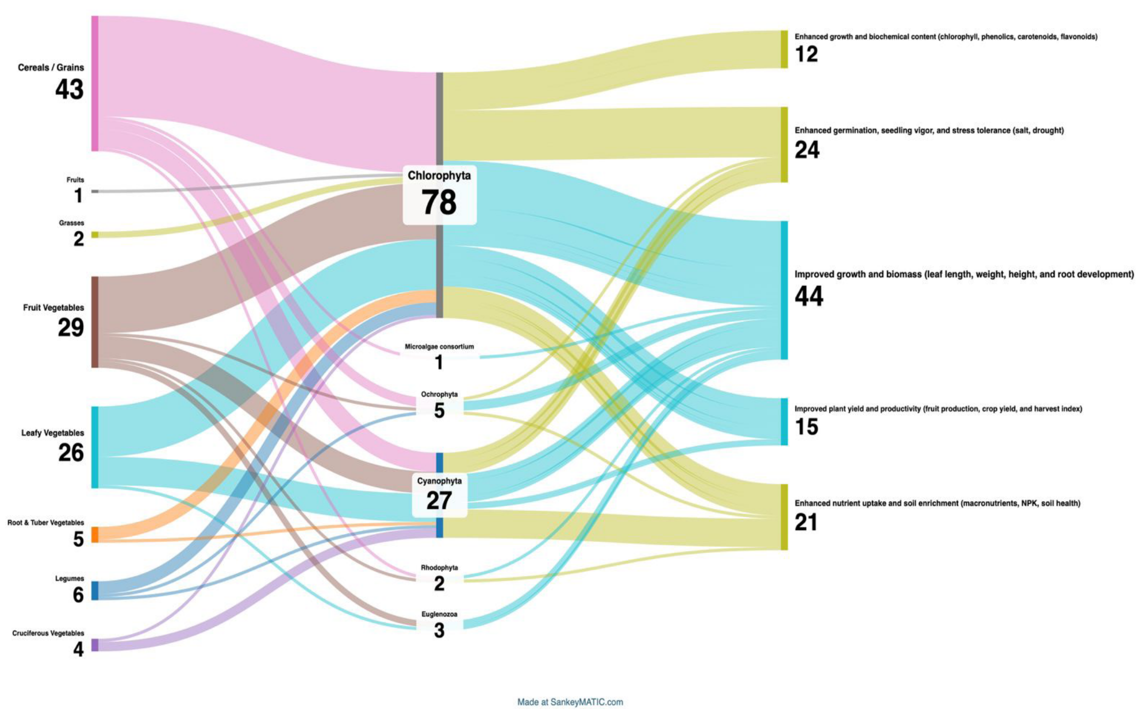

Figure 9. Sankey diagram of crops, microalgae or cyanobacterial strains and their main effects on crop production.

In Colombia, a country with a wide diversity of agroecological zones, it is essential to explore sustainable alternatives for its agricultural sector. Colombia faces significant challenges in ensuring food security and environmental sustainability, mainly due to conventional farming practices that may compromise the integrity of its ecosystems and the well-being of its farmers (62). Therefore,

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transitioning towards more sustainable agricultural practices that ensure food security and environmental protection in Colombia is crucial (63). In the Colombian context, Table 4 summarizes the studies carried out in the country on using microalgae as biofertilizers and biostimulants. These studies, which show the growing interest in exploring sustainable and biotechnological alternatives for agriculture, highlight the diversity of methodological approaches applied. A comparative analysis of these studies is recommended to identify patterns, limitations, and opportunities for future research in this emerging area.

Table 4. Relevant articles on the use of microalgae as biofertilizers in Colombia

Crop	Microalgae/ cyanobacteria	Effects	Form of application	Author
Wheat	*Chlorella sorokiniana*	Increase in plant length and improvement in total biomass	Liquid Extract	(64)
Gulupa	*Microcystis aeruginosa, Synechococcus rubescens, Cyanobium gracile*	The application of the cyanobacteria consortium and the organic fertilizer increased plant length.	Liquid extract	(65)
Stevia and eggplant	*Limnospira máxima*	Greater leaf area and plant height in both crops	Liquid extract	(66)

Results and discussion

The initial studies conducted in 2011 focused on three principal axes: first, the toxic effects of carbaryl on the cyanobacterium *Calothrix brevissima* used as a biofertilizer in rice cultivation were evaluated by subjecting it to various concentrations for 21 days (67); secondly, the potential of cyanobacteria in areas as diverse as food, agriculture, wastewater treatment and biofuel production was analyzed, with special emphasis on the generation of secondary metabolites with therapeutic value (68); and thirdly, the relevance of microbial communities mainly "Plant Growth-Promoting Rhizobacteria" PGPR and cyanobacteria to improve the stability, productivity and sustainability of agroecosystems was highlighted (69). Subsequently, in 2014, a review article evidenced that biofertilizers based on PGPR, mycorrhizae, and cyanobacteria optimize nutrient uptake, promote growth, and activate key genes in natural plant defenses, thus opening the route to more sustainable agriculture (70). The following year, in 2015, Choudhary and Dhar addressed molecular and genetic techniques that enhance nutrient bioavailability, contributing to the enhancement of agricultural sustainability (71). 2016 marked the beginning of research to identify eco-friendly alternatives to improve crop nutrition and protection by applying microalgae and cyanobacteria. This year, the efficacy of microalgae biomass cultivated in wastewater, used as a biofertilizer and biostimulant in wheat, was initially evaluated (14). This line of research was expanded to include diverse inputs from algal extracts to by-products such as shrimp shells, and the potential of microalgae as a slow-release organic fertilizer in crops such as tomatoes was explored (72). Additionally, biostimulant properties were identified in the microalga *Acutodesmus dimorphus*, and the integral role of cyanobacteria in processes such as phosphorus solubilization, development of certified organic growing media, and crop protection was analyzed (22).

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During the year 2017, research was oriented towards the evaluation of ecological alternatives through field trials; the efficacy of biofertilizers based on cyanobacteria in corn crops (73) and the usefulness of algal extracts as biostimulants to favor plant growth were demonstrated (74). Likewise, cyanobacteria's agroecological and biotechnological impact was explored, including the design and evaluation of an algal biofilm reactor intended for wastewater treatment, which allowed for characterizing the biomass generated and proposing diversified applications (75). In 2018, the research line adopted a multidisciplinary approach: on the one hand, the potential of microalgae and cyanobacteria as biofertilizers to optimize growth and productivity in crops such as rice was examined (13); on the other hand, specific compounds, such as *Dunaliella salina* exopolysaccharides, were investigated to confer salt stress tolerance in tomatoes (15). Incorporating these organisms in circular economy strategies, along with evaluating the impact of technologies based on blue-green algae and the role of nitrogen-fixing cyanobacteria, broadened the prospects for application in the agricultural sector (76).

In 2019, a comprehensive approach started with identifying the biocontrol capabilities of microalgae and cyanobacteria against fungal pathogens (77). From there, progress was made in applying these inputs in producing biofertilizers and biofuels derived from waste and wastewater, targeting key crops such as corn and date palm (78). In addition, the optimization and valorization of by-products were further explored, also analyzing the influence of environmental factors such as CO_2 and metal-rich wastewater on the productive potential of cyanobacteria under adverse conditions (79). The year 2020 was characterized by an integrated approach combining advanced biotechnology and microbial resource use to promote sustainable agriculture (80). At this stage, recombinant DNA was first explored to enhance biofertilizer production, thus facilitating the use of microalgal biomass from crops and wastewater (81). Next, microalgal extracts and polysaccharides were evaluated as biostimulants, showing improvements in the growth of crops such as tomatoes (82) and optimization in the availability of phosphorus and other nutrients in the soil (35). In addition, the ability of species such as *Nostoc muscorum* to mitigate abiotic stress was investigated, reinforcing their potential in crop adaptation to adverse environments (83). These approaches were integrated into a strategy ranging from improving agricultural productivity to strengthening food security and reducing greenhouse gas emissions (84).

In 2021, the research revealed a highly multidisciplinary approach to integrating sustainable solutions into modern agriculture. The potential of biofertilizers derived from microalgae and cyanobacteria was examined (85), assessing both their influence on plant growth and productivity and their ability to improve resilience to abiotic and biotic stressors, such as cadmium exposure (86). Studies included analysis of both above and below-ground responses of crops in semi-arid areas (87), bioremediation of soils and wastewater (88), and optimization of culture media for large-scale production of protein-enriched biomass and biostimulants using agricultural wastes as feedstock (89). During 2022, research focused on the development and integration of solutions based on cyanobacteria, microalgae, and macroalgae, using wastewater as a medium for the production of biofertilizers and biostimulants, thus helping to reduce dependence on inorganic fertilizers (90). Operational systems, such as photobioreactors and raceway-style tanks, were

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implemented to evaluate the effectiveness of these inputs in improving soil quality, crop yields, and environmental resilience (91).

Additionally, bioremediation strategies aimed at wastewater treatment, mitigation of atmospheric emissions, mineral mobilization, and abiotic stress management in plants were evaluated, integrating analysis of technology acceptance by farmers and promoting a circular economy approach (92). In 2023, the research was oriented towards a comprehensive and cutting-edge transformation utilizing by-products and microorganisms for sustainable agriculture (93). The impact of dehydration on the physicochemical properties and non-directed metabolic profile of *Nostoc calcicola* Bot1 was further analyzed, establishing a robust analytical basis for assessing the influence of adverse environmental conditions (94). In parallel, zero-waste strategies in producing and utilizing *Arthrospira platensis* were explored, highlighting its duality as a protein source and biostimulant (95). Subsequently, the focus was diversified in the search for alternatives to chemical fertilizers through the implementation of consortia and the synergy between calcareous algae and cyanobacteria, promoting metabolic alterations favorable to plant growth. In addition, wastewater treatment technology was integrated with the cultivation of microalgae and the production of high value bioproducts, directly affecting the reduction of the carbon footprint and the mitigation of greenhouse gas emissions (96, 97).

Finally, a multidisciplinary and circular approach was adopted in 2024, starting from the fundamental analysis of the physicochemical and metabolic properties of key microorganisms such as *Chlorella* sp., and various cyanobacteria subjected to stress and dehydration conditions and extending to the design of integrated bioremediation and biorefinery systems (7). Heterotrophic upcycling strategies applied to wastewater from hydroponics, combined with carbon and regulator inputs, such as indole acetic acid, were explored to transform these by-products into high-quality biomass (92). At the same time, microalgae-bacteria consortia were developed, and methods were evaluated for the selection and potentiation of strains with biostimulant activity, confirmed by life cycle studies and meta-analytical analysis, aimed at optimizing soil fertilization, promoting crop growth and improving resource use efficiency (98). This integrative process seeks to create zero waste systems that interconnect wastewater treatment biofertilizer production and implement emerging technologies, moving towards a more sustainable and resilient agriculture (99).

The application of microalgae in suspension is the simplest, most economical and profitable option for biofertilizers, since it allows cultivation, harvesting and direct application of the biomass without complex processes, reducing costs and energy, and favoring biological action in nitrogen fixation and improvement of soil microbiota (93). In comparison, cell extracts, despite offering faster growth thanks to their bioactive compounds, require cell disruption procedures and rigorous dosage control, which increases their cost and complexity (94). The choice between the two methods will depend on the type of crop, soil conditions and specific objectives, with suspension being the preferred strategy for large-scale applications (95).

Currently, most research on the use of modified microalgae is in experimental or pre-commercial phases, where advances have been made in biosynthetic efficiency and the production of specific compounds. However, these developments face regulatory challenges and social acceptance problems for their eventual commercialization. Commercial approvals must not only demonstrate

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efficacy, but also ensure that the use of modified organisms does not pose ecological or human health risks (100).

In summary, the review of the research trajectory in the field of microalgae and cyanobacteria shows a significant evolution in the development of bio inputs and sustainable solutions for agriculture. The advances described offer a solid foundation for future research that, through the integration of multidisciplinary strategies and process optimization, will be able to overcome current challenges and transform opportunities into impactful innovations for food security and environmental sustainability.

Conclusions

The upward trend in annual scientific production between 2010 and 2024 is evidence of the growing interest and intensification of research on applying microalgae as bio inputs in agriculture. This increase is reflected not only in a greater number of research and publications but also in the advancement of technological projects that seek to take advantage of the potential of microalgae to improve soil quality and promote sustainable agricultural practices.

The present review has highlighted the considerable potential of microalgae and cyanobacteria to transform sustainable agriculture. Their ability to synthesize a wide range of bioactive compounds, optimize nutrient uptake, enhance stress tolerance, and contribute to environmental remediation positions them as promising alternatives to synthetic agrochemicals. However, to realize these benefits, overcoming challenges related to large-scale production, profitability, and transformation processes is imperative, which is essential to ensure their commercial viability.

Concerning the situation in Colombia, future research should focus on delving deeper into the physiological and biochemical mechanisms by which these organisms drive crop growth and improve resilience to stress. It is crucial to optimize cultivation and processing techniques, as well as to develop extraction and purification methods that are adapted to local agroecological conditions. Furthermore, exploring innovative applications, such as the formulation of biopesticides and the implementation of bioremediation processes, will broaden the spectrum of usefulness of these resources in the Colombian agricultural sector.

Finally, interdisciplinary collaboration between researchers, farmers, and policymakers is essential to translate scientific advances into practical and effective solutions. Integrating microalgae cultivation with wastewater treatment and selecting strains adapted to diverse agroecological zones will enable the establishment of customized strategies that transform current challenges into opportunities for innovation. Together, these efforts will strengthen food security and promote long-term environmental sustainability.

Future challenges include the possibility of uncontrolled releases of modified microalgae and their possible long-term effects on the environment, which underscores the need to establish containment measures and biosafety protocols. In addition, constant updating of regulations is required to align with the rapid advances in biotechnology. In this scenario, it is essential to promote an open dialogue between scientists, regulators and society to balance innovation with environmental protection and food safety.

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