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Review article

Microalgae research worldwide

Jose Antonio Garrido-Cardenas[a], Francisco Manzano-Agugliaro[b], Francisco Gabriel Acien-Fernandez[b,*], Emilio Molina-Grima[b]

[a] Department of Biology and Geology, University of Almeria, 04120 Almeria, Spain
[b] Department of Engineering, University of Almeria, 04120 Almeria, Spain

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ABSTRACT

In this paper, worldwide research trends in the microalgae field are analyzed based on a bibliometric study. We have reviewed the number of publications and their distribution, as well as the most relevant journals and keywords, to determine the evolution and latest tendencies in this field. The results confirm that this is a fast-growing area in terms of the number of publications. The most relevant journals on this subject are Bioresource Technology and Algal Research. Although the majority of papers come out of the USA, the institutions with larger number of publications are actually located in China, France and Spain. The most frequently cited strains are *Chlorella* and *Chlamydomonas*. The main keywords that appear in over 1000 articles are generally related to microalgae cultivation applications such as 'biomass, biofuel, and lipids' while others are related to the methodology; for instance, 'bioreactor'. Of all the keywords, 'biomass' stands out, as it appears in almost 20% of publications. Bibliographic analysis confirms that Microalgae Biotechnology is a very active field, where scientific productivity has exponentially increased over recent years in tandem with industrial production. Therefore, expectations are high in this field for the near future.

1. Introduction

Microalgae biotechnology is a relatively new research area that has increased exponentially over the last few years in parallel with the rapid appearance of facilities and microalgae-based products. This field generally includes both eukaryotic microalgae and prokaryotic cyanobacteria - although they are biologically quite different microorganisms, the fundamentals of their production are similar, as are the type of products/applications for which they are used. Today, these microorganisms are used to produce: (i) high-value compounds, such as carotenoids, polyunsaturated fatty acids and phycobiliproteins, (ii) whole biomass that form part of nutraceuticals, foods and feeds, (iii) extracts or processed biomass to produce biofertilizers, which are also being proposed for biofuel production, or (iv) the living microorganisms used in bioremediation processes for wastewater, soils and flue gases [1]. Whichever final application is being considered, the whole production process must be specifically designed to fit within it. Defining a general technology or process that can be used with any application is not possible.

Although microalgae have been described in biological processes over many centuries, the first studies on microalgae production under controlled conditions started in the 1950s [2]. Over the following years, different types of photobioreactors were proposed, such as raceways [3] and tubular [4]; these reactors are still the most widely used. The first strains to be studied included *Chlamydomonas*, *Chlorella* and *Spirulina*, the latter two being the most cultivated worldwide today. *Chlamydomonas* has been extremely well studied from a physiological and genetic standpoint; it is a model microorganism in the study of microalgae photosynthesis and molecular biology. The first products obtained from microalgae were limited to the whole biomass, which was included in human foodstuffs or as feed for aquaculture. Since this time, the evolution of microalgae biotechnology has been based on four pillars: (i) looking for new strains capable of easy and rapid growth, which contain novel valuable compounds, (ii) knowledge of the strain's biology and the mechanisms regulating cell performance, (iii) improving production systems both in terms of efficiency and capacity, and (iv) developing new markets and products [5].

Although thousands of microalgae strains are available in numerous culture collections worldwide, only a few have been studied in detail. Strains like *Dunaliella salina*, as a source of beta-carotene, or *Haematococcus pluvialis*, as a source of astaxanthin, are good examples of new strains that have finally achieved commercial-scale success [6].

* Corresponding author.
E-mail addresses: jcardena@ual.es (J.A. Garrido-Cardenas), fmanzano@ual.es (F. Manzano-Agugliaro), facien@ual.es (F.G. Acien-Fernandez), emolina@ual.es (E. Molina-Grima).

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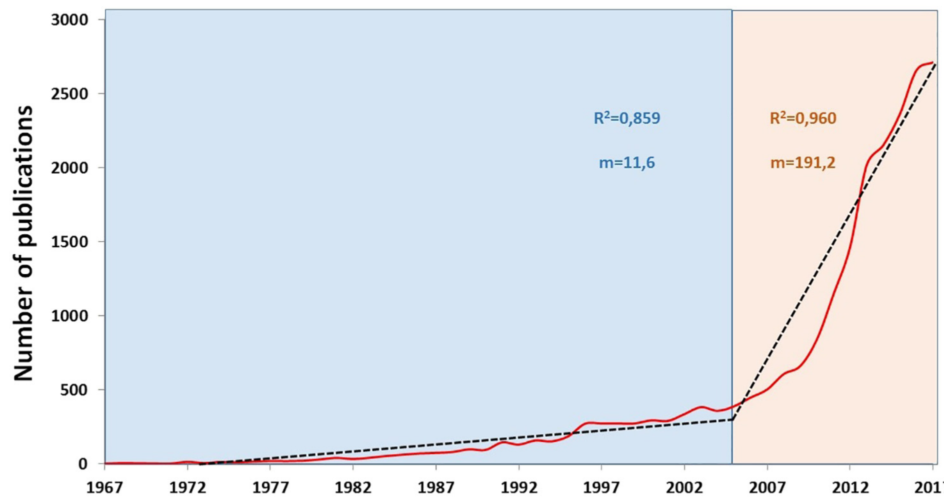

Fig. 1. Trend in the number of publications from 1970 to 2017.

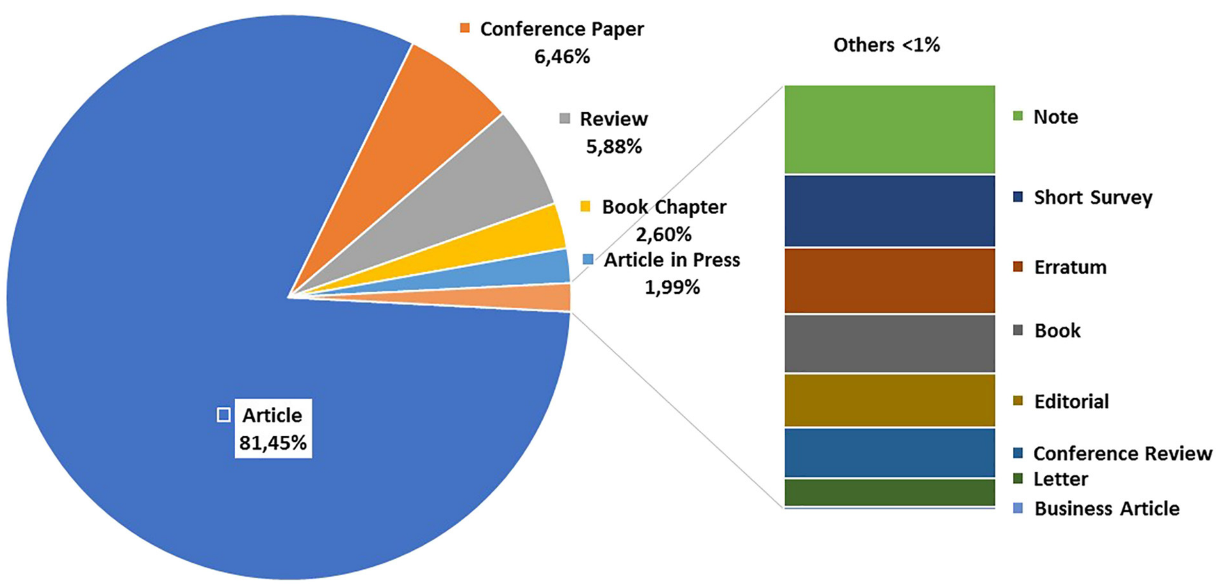

Fig. 2. Distribution of document types for microalgae.

However, hundreds of additional strains have been reported in the literature as sources of carotenoids. The reason why these strains have not achieved commercial-scale production is usually related to a lack of strain robustness or low productivity under outdoor conditions. Therefore, only strains capable of performing adequately under a wide range of culture conditions, including tolerance to adverse short-term conditions, can be produced outdoors. New strains that are now produced at large-scale include *Euglena* and *Porphyridium*, even though these strains' production capacity is much lower; this is because they are mainly used as food supplements or in cosmetics [7]. In addition, new seawater strains have been incorporated into the portfolio of commercially produced strains due to the aquaculture sector's requirement for high quality aquafeed for fish larvae and crustaceans - these include *Nannochloropsis*, *Tetraselmis*, *Isochrysis* and *Chaetoceros* amongst others [8].

Concerning strain biology and genetics, great effort has been made in recent years to elucidate the mechanisms involved in synthesizing target compounds as a prior step to increasing their accumulation in the biomass. Examples of this are the production of fatty acids and astaxanthin, to name but two [9]. In this area of research, methodologies developed for other organisms have usually been translated to microalgae but unfortunately this strategy has not been successful given the particularities of microalgae cells (their cell wall, etc.). Initially, selection strategies were used to obtain super-producing strains but the improvements achieved by this strategy were limited. Subsequently, mutation-selection strategies were tried but random mutagenesis usually reverts to the wild type after a few generations making this strategy similarly inefficient. In the last few years, advances in molecular biology have allowed specific mutation techniques to be applied that obtain stable overproducing strains [10,11]. Further developments in this field could greatly improve the performance of current or new strains.

With regard to production technology, different reactor types have been proposed such as α-reactors, vortex reactors, flat-panel reactors, thin-layer reactors, vertical biofilm reactors, algae-disc reactors, etc.; however, still the most extensively used reactors are raceway and tubular types [12,13]. The main issue for photobioreactors is maximizing strain performance to provide optimal conditions for the strains at minimal cost. Optimal conditions are usually dependant on the culture medium, the temperature and pH, but especially on light availability to the cells. Calculating light availability in any photobioreactor has been a challenge although this has been solved by introducing the concept of average irradiance [14]. Providing optimal conditions at the small scale is possible using a multitude of different reactor designs, but

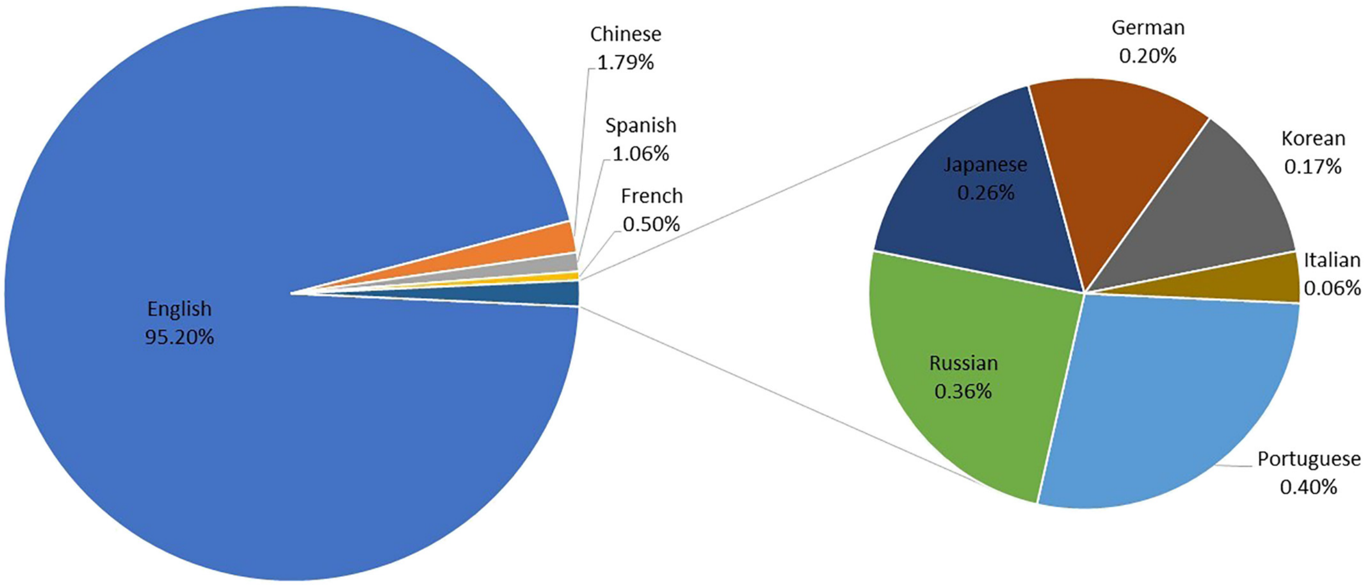

Fig. 3. Principal languages used and number of publications.

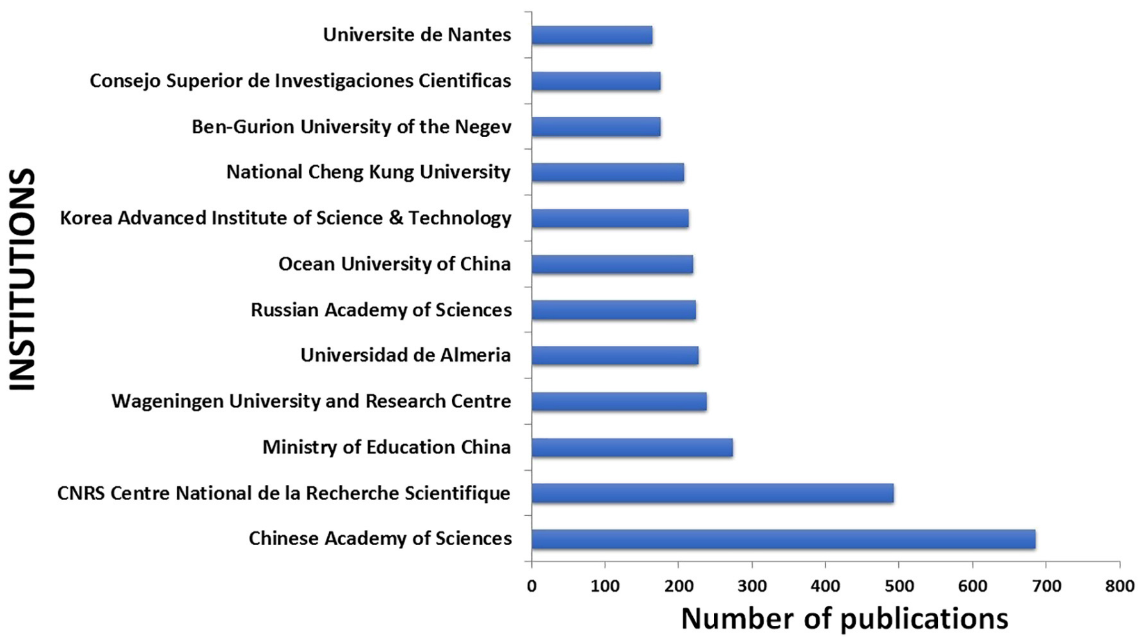

Fig. 4. Top 12 institutions by number of scientific publications on microalgae.

when increasing the reactor size it is usually not possible to maintain such conditions. The main drawbacks in large reactors are related to the inability to control temperature, inadequate mixing, excessive power consumption and poor mass-transfer capacity [15–18]. In addition to photobioreactor design, the harvesting strategy is also a major factor determining the suitability of large-scale microalgae production; this step accounts for up to 30% of the overall production cost [19]. The challenge is always to achieve the highest production capacity at minimum cost; however, to achieve this objective, different technologies and strategies need to be used according to the particular location [20,21].

At the beginning of the 21st century, the proposition that microalgae could be a possible source of biofuels, along with the high oil price at that time, motivated large energy companies to take an interest in microalgae biotechnology, investing significant amounts of money to pursue that objective. Highly relevant papers were published that established the potential for these technologies [22,23]. However, the yield from real production systems was far from the theoretical values, owing to bottlenecks that still limit biodiesel production from microalgae [24]. Unfortunately, adequate bioenergy production from microalgae remains unrealized. Nevertheless, the sizeable investment made over those years generated a leap in technology and production capacity that is now facilitating an expansion in commercial microalgae applications. Hence, in recent years, the technology has been improved to such an extent that, today, there are industrial facilities for both tubular and raceway reactors covering hundreds of hectares. Nevertheless, most of the microalgae biomass produced worldwide is still produced in open raceways [25]. The production cost of microalgae biomass has dropped to 5 €/kg and can be reduced yet further to below 1 €/kg when coupled with wastewater treatment using CO_2 capture from flue gases [20]. Consequently, new microalgae applications focused on wastewater treatment are now being scaled up for industrial

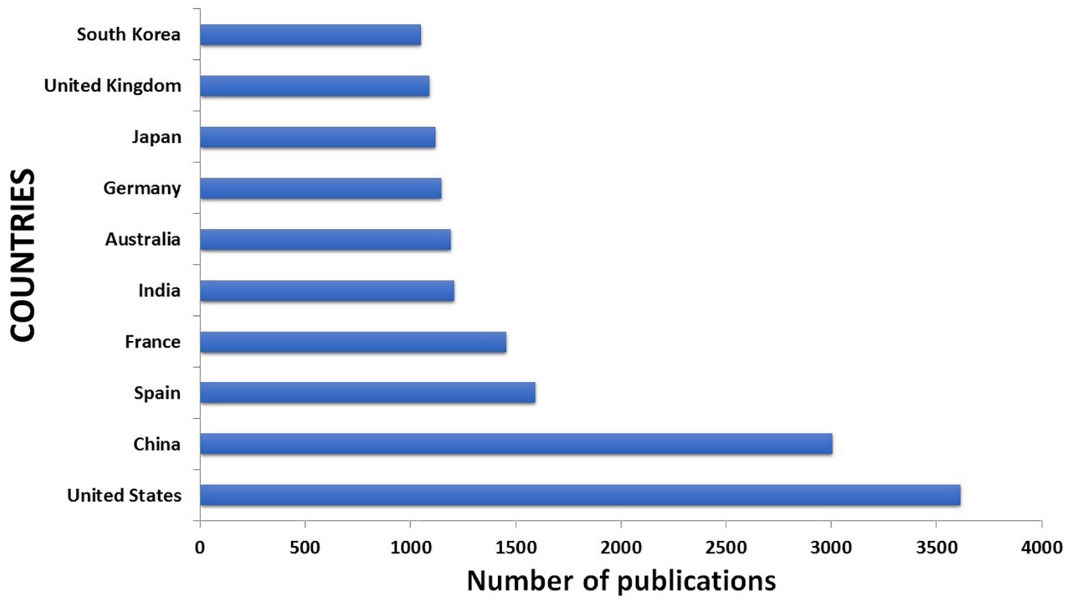

Fig. 5. Top 10 countries in scientific output on microalgae.

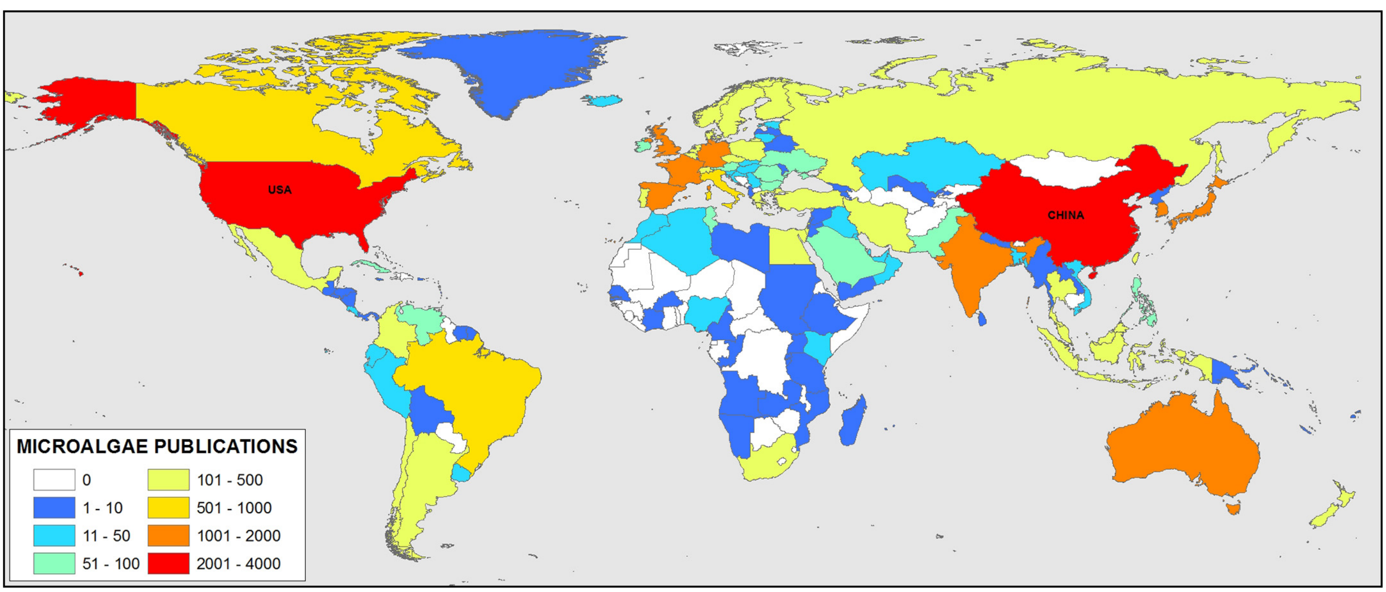

Fig. 6. World map with main countries and their number of scientific publications on microalgae. The red color indicates a greater number of publications, the blue color indicates the smaller, and white when it does not exist. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Publication distribution by countries.

Country	No. publications	Population (million inhabitants)	No. pub/mill. inhab.
USA	3615	326,747	11.06
China	3005	1,388,232	2.16
Spain	1593	46,070	34.58
France	1456	64,938	22.42
India	1206	1,342,512	0.90
Australia	1191	24,641	48.33
Germany	1145	80,636	14.20
Japan	1120	126,045	8.89
UK	1091	65,511	16.65
South Korea	1049	50,705	20.69

processes, the resultant cheap biomass produced being suitable for use in low-value markets such as biofertilizers. As a result, microalgae biotechnology will certainly continue to increase over the next few years, with both the technologies and products being improved and extended to new applications.

The major bottlenecks limiting the expansion of microalgae biotechnology are the high production costs and the small-scale of current production systems. Consequently, less than 20,000 t of biomass are produced worldwide, at a cost above 5 €/kg [7]. This high production cost limits microalgae biomass applications, mainly to high-value markets such as human foods and some aquaculture specialties [26]. The low production capacity means that the food industry does not consider this biomass as being realistically available for inclusion in large-scale food production processes, compared to other conventional materials, such as cereals or vegetables, which are available in much greater quantities. To solve these problems, the production capacity

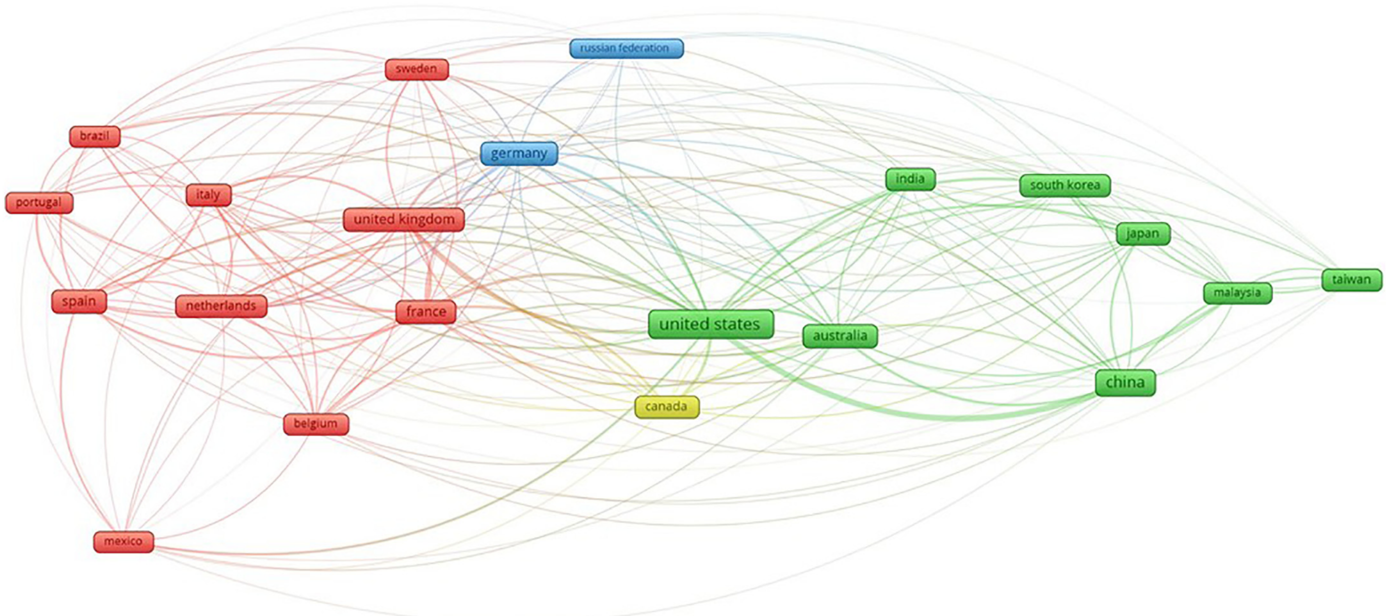

Fig. 7. Communities of countries and their associations in publications on microalgae.

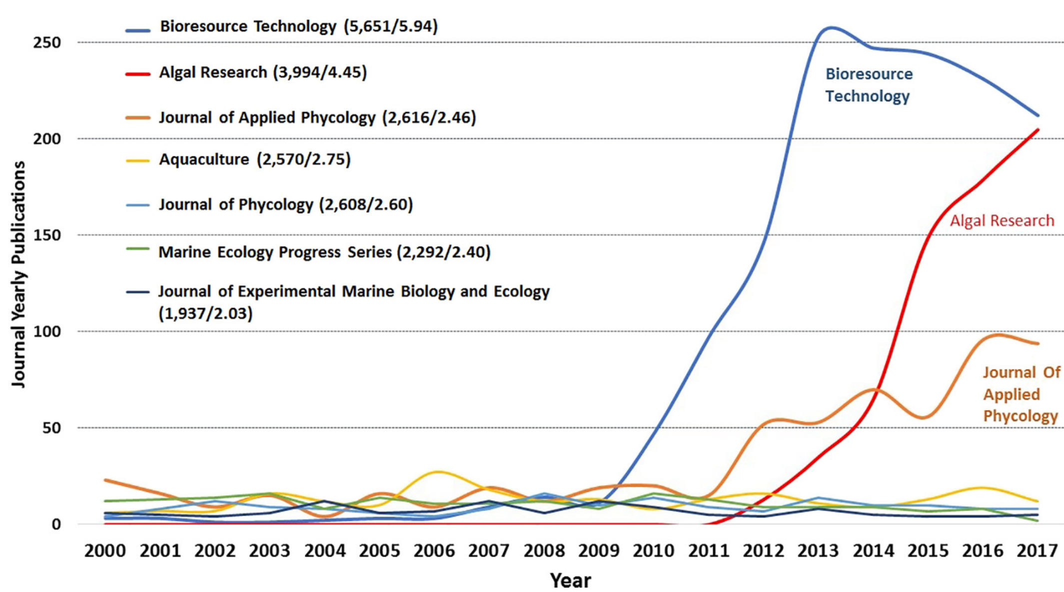

Fig. 8. Trend for the main sources in the number of publications from 2000 to 2017.

must firstly be increased several orders of magnitude by developing more robust and efficient production systems. Secondly, the production cost must be reduced by increasing the production capacity. However, the larger reduction will be achieved by coupling biomass production with nutrient recovery from residuals. Of course, these advances must be further supported by continuous improvements in the performance of the microalgae strains produced, not only in terms of productivity and efficiency but also in biochemical composition and hence the value of the biomass produced.

The objective of this manuscript is to analyze the worldwide trends in microalgae research using the research output from Scopus (https://www.scopus.com) to highlight any new perspectives on the topic. For this purpose, a bibliometric study can be used. Bibliometry consists of using tools and methodologies to analyze and evaluate the results of all the literature generated on a research subject [27]. Using these tools, a variety of conclusions can be drawn such as: identifying the main institutions and the most important researchers in a research field, evaluating the most important milestones over the history of a scientific field, or predicting trends or scientific fads through the study of the evolution of the produced literature [28]. Over recent years, many bibliometric analyses have been carried out in different scientific areas that have shown the great usefulness of this methodology [29–31].

2. Methodology

In the present study, a complete search of the Elsevier Scopus database was carried out using [TITLE-ABS-KEY (microalga*)] as the search query. The search resulted in 22,278 documents being obtained after limiting the search timescale from 1970 to 2017. It should be noted that if different search parameters were used, the results would vary. It should also be in mind that this method may have some gaps due to the introduction of keywords, by the author or the editorial, that do not fit the subject matter of the articles. The obtained results were processed by grouping keywords with identical meanings and

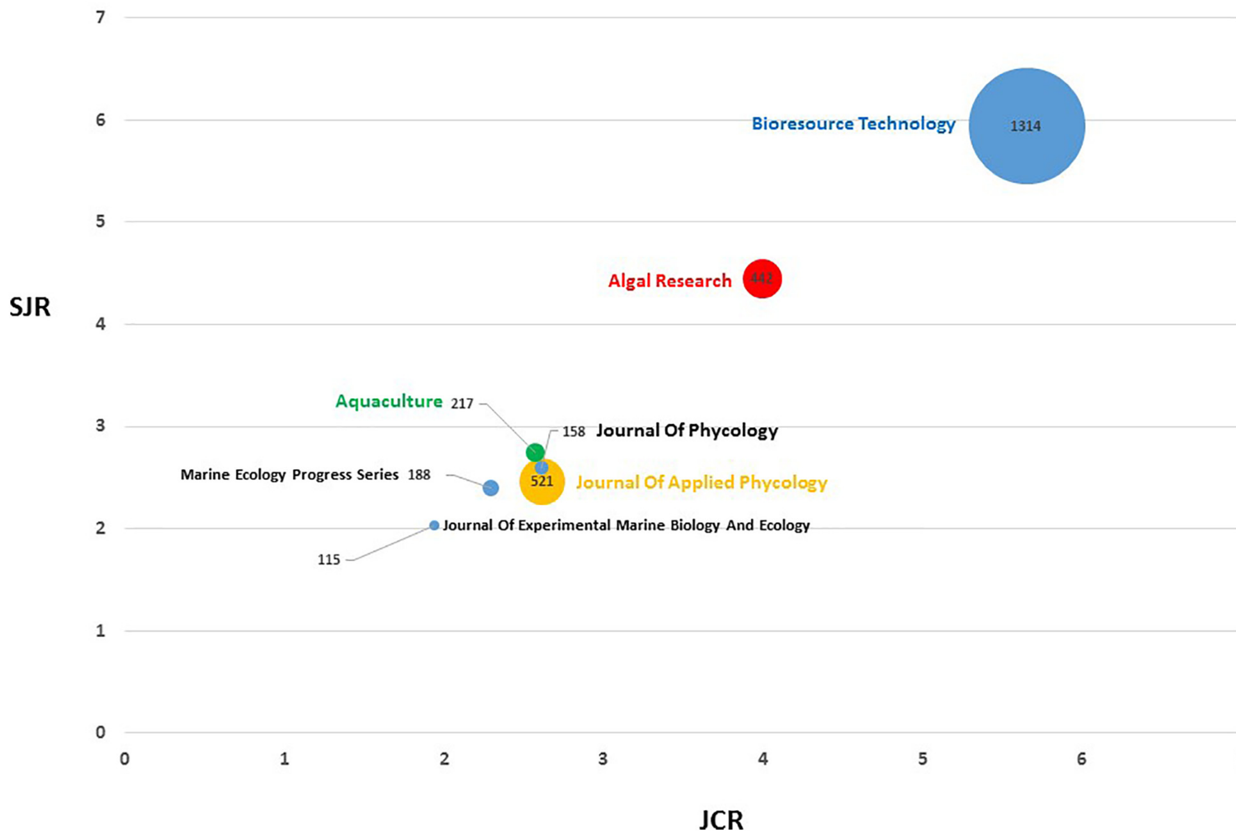

Fig. 9. Total number of publications related to the value of the Impact Factor in JCR (Journal Citation Report), and the CiteScore in SJR (SCImago Journal Rank).

discarding those that did not contribute to this study; for example, 'article'. Also, the most important data were selected, which were represented in a way to make them easier to understand. The aspects studied were: the number of publications per year, the distribution of publications by institutions and by country, the sources and the keywords. In the study of complex networks, a community can be defined as a set of nodes that are more densely connected to each other than to the rest of the network. Communities' detection was carried out using the VOSviewer software tool (http://www.vosviewer.com/). This software allows one to elaborate graphs in which each country or keyword is represented by a node, and the connections between two nodes represent the collaboration between the two terms that the nodes represent.

The records obtained were conveniently processed using spreadsheets and a specific open-source coding tool, OpenRefine (http://openrefine.org/). This application "is a standalone desktop application initially developed by Google for data clean-up and transformation to other formats". The methodology allows for the straightforward analysis of unsorted, conflictive or disorganized text. Consequently, highly satisfactory results were obtained that would otherwise be nearly impossible to achieve given the extensive size of the database. OpenRefine was used for the analysis of keywords and allowed us to eliminate duplicate records or group different representations of the same reality. This methodology has been used successfully in other bibliometric studies [32,33].

3. Results

3.1. Evolution of the scientific output

Fig. 1 shows the evolution of the number of publications from 1970 to 2017. Before 1970, the number of publications on microalgae was low, while 2017 is the last year for which complete data are available. The results show that there were two clear trends over this period. The first was from 1970 to 2005 whereas the second began in 2005 and continued until the end of the study period. Both trends can be adjusted to straight paths with similar R^2 coefficients but very different slope values. The first has a slope value of 11.6, while the second slope is more than fifteen-times greater, at 191.2. These slopes represent the increase in the number of publications per year, showing that, although interest in microalgae research increased throughout the studied period, it rose dramatically from 2005 onwards. The results also show that, in the last ten years, research in this field has continued to grow, reaching more than 2700 publications a year by 2017; this being a great indicator of microalgae's importance in current research.

Most publications on microalgae (81.45%) are articles. In second and third position, sharing similar values are conference papers and reviews; reviews are understood to be manuscripts that highlight the state of the art in a field without using original material. These two document types represent 6.46% and 5.88% of microalgae publications, respectively (Fig. 2). Other documents appear at a lower frequency, such as book chapters, notes or short surveys. The relative importance of books/articles/etc. is similar from other research fields. Because most of the studies were articles published in international journals, which are predominantly English-speaking, the most commonly used language was English, found in 95.45% of documents. Fig. 3 shows the breakdown of the ten main languages used (one should note that a single document might be written in more than one language).

3.2. Publication distribution by countries and institutions

Fig. 4 shows the top twelve institutions, accounting for more than 150 publications. From these top institutions, six are European (two Spanish, two French, one Russian and one Dutch) and six are non-European, principally Asian and Middle-Eastern (three Chinese, one Korean, one Taiwanese and one Israeli). However, if the analysis is

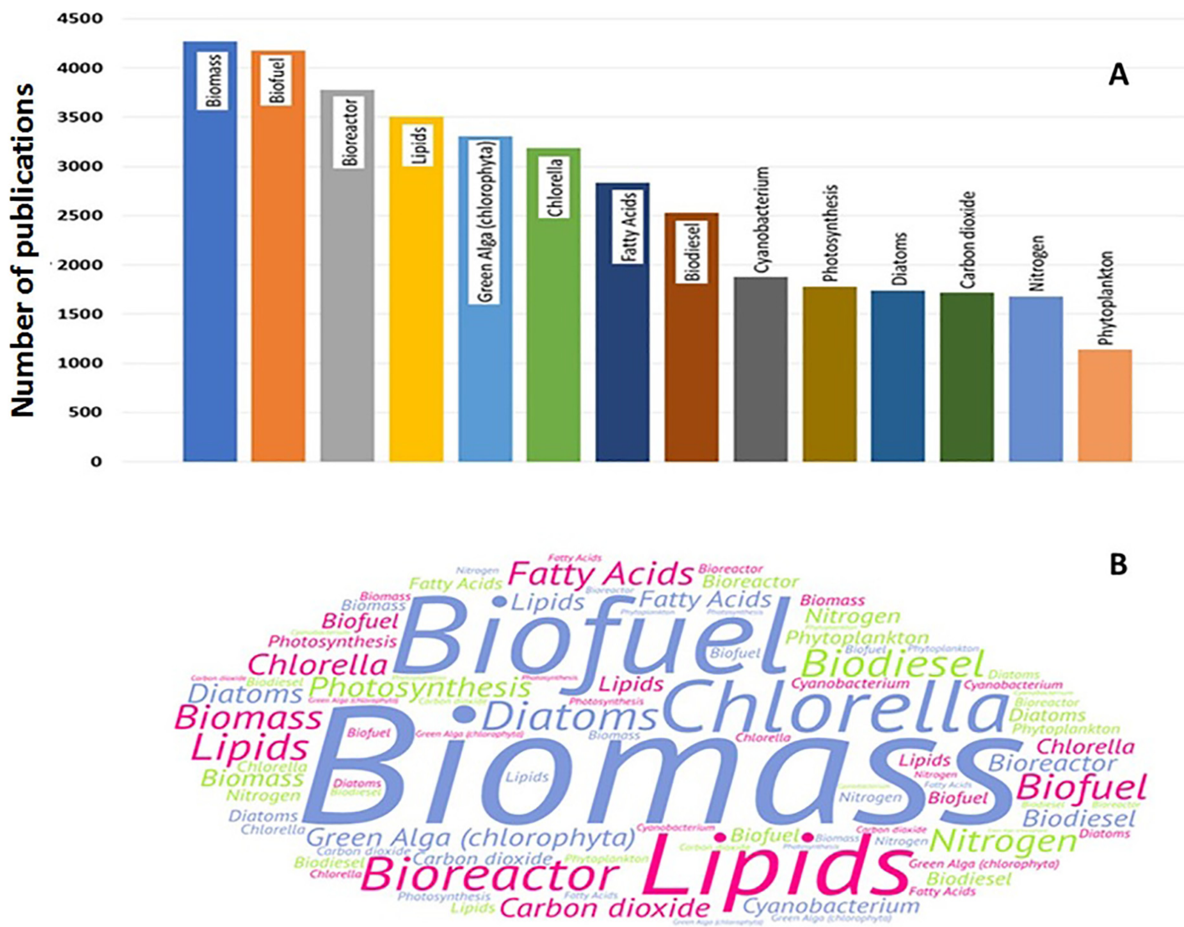

Fig. 10. Different representations of keywords. A) Bar chart. B) Cloudword.

performed by country rather than by institution (Fig. 5), the results show that first place is occupied by the USA, followed by China, Spain and then France. Looked at from this perspective, the USA leads the ranking in the number of publications on microalgae with more than 3500 articles over the studied period; yet they still do not have any institution in predominant positions. This is explained because there are up to 70 American institutions with at least 20 publications on microalgae each, while there are only 55 Chinese, 35 French and 29 Spanish institutions with an equivalent number. In these latter countries, the weight of research into this subject rests mainly on single institutions - the Chinese Academy of Sciences in China, the CNRS (Centre National de la Recherche Scientifique) in France, and the University of Almeria in Spain - whereas in the USA, interest in this area is far more homogeneously distributed between research centers, or is less specialized in this field. Other countries such as Australia and India are well positioned in the ranking for the number of publications but their institutions are not amongst those that produce more scientific literature since their situation is similar to the USA.

Fig. 6 shows a world map in which the scientific production of each country is color highlighted. It can be observed that, geographically, this field of study is mainly relevant in the USA, China, Japan, Spain, France, Germany, United Kingdom, and Australia. Using the population data from http://www.worldometers.info/world-population/population-by-country/, the value of the scientific production by country was normalized (Table 1). The results show that the top position goes to Australia with more than 48 publications per million inhabitants, followed by Spain with more than 34. Countries such as China or India, with populations over one billion people, occupy the last positions in this normalized ranking.

Fig. 7 shows a distribution by communities of the countries that have published at least 300 articles on microalgae. The 21 countries that appear in this figure are distributed over 4 large communities. The first community is formed by Asian countries, along with Australia and the USA. The second is formed by European countries, along with Mexico and Brazil. The third community is formed by Germany and Russia, while Canada constitutes a community unto itself. Globally, one can observe the central role played by the USA, and the large number of connections that exist between the countries with the greatest potential. Of these, it is remarkable how many connections exist between researchers from China and the USA in terms of collaborations on microalgae publications.

3.3. Sources

Fig. 8 shows the evolution of the seven journals that published at least 100 articles on microalgae from 2000 to 2017. The results show that there are four journals that have kept their scientific production practically constant since 2000: *Aquaculture*, *Journal of Phycology*, *Marine Ecology Progress Series*, and *Journal of Experimental Marine Biology and Ecology*. On the other hand, three journals have shown a positive evolution in their scientific production, especially from the year 2009: *Bioresource Technology*, *Algal Research* and *Journal of Applied Phycology*. In absolute terms, *Bioresource Technology* is the fastest growing journal while in percentage terms, *Algal Research* is the journal with the greatest tendency for growth in this scientific field, reaching the second position overall in 2017, whereas the former has a declining trend in publications in this field.

In addition, Fig. 9 shows the total number of published items related to the value of the Impact Factor from the JCR (Journal Citation Reports) (calculated from the Web of Science database, formerly part of

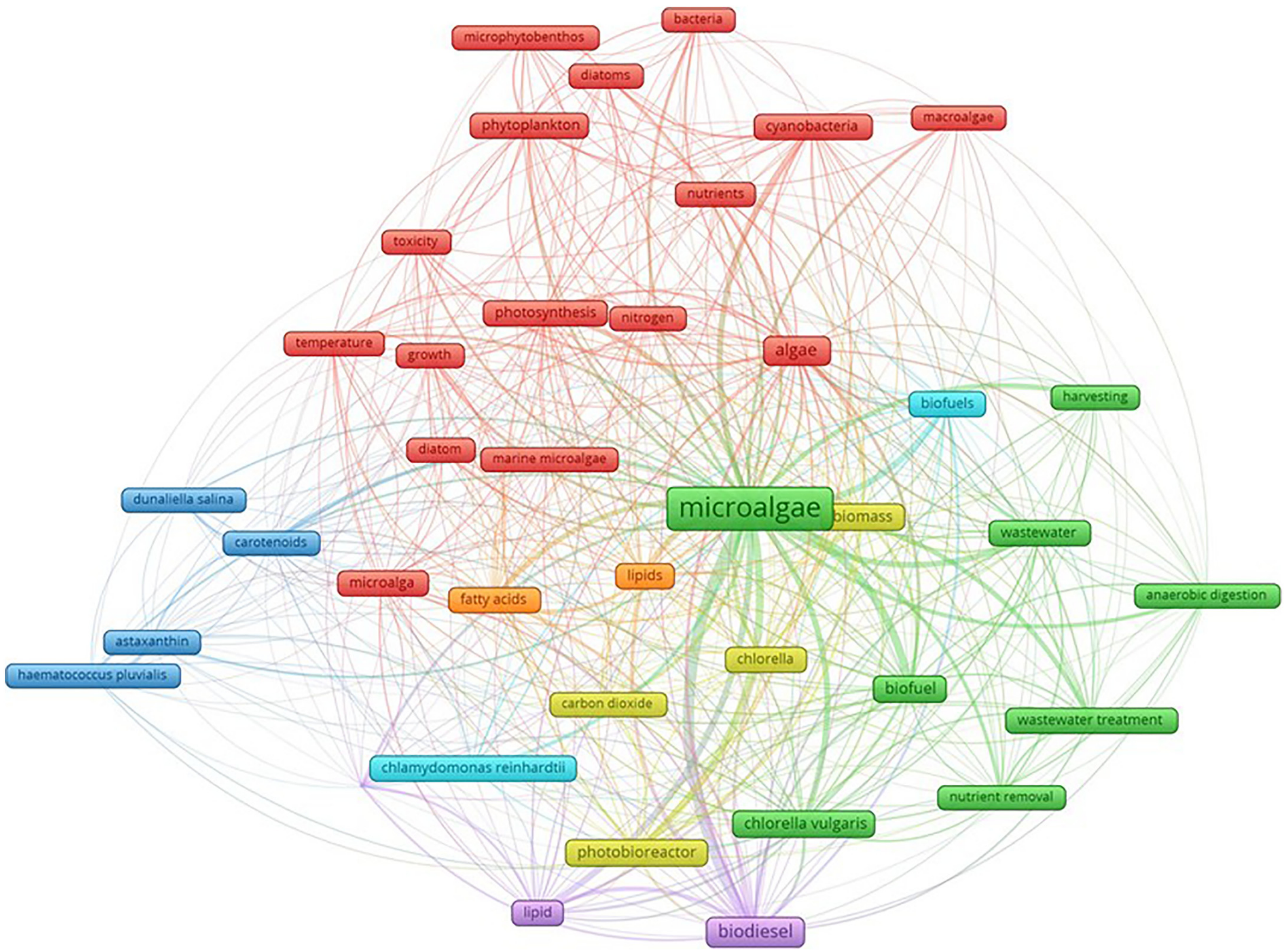

Fig. 11. Communities of keywords and their associations in publications on microalgae. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Thomson Reuters) and the CiteScore from the SJR (SCImago Journal Rank) (calculated by Elsevier from the Scopus database). One can see how both indexes follow the same trend, being good indicators of the citations received by the journals. The relationship between the number of published items and the impact indexes is observed mainly in the first two journals from the ranking *Bioresource Technology* and *Algal Research*, whereas for the other journals, this is no longer observed.

3.4. Keyword analysis

To carry out the analysis of keywords we first discarded all those that contributed nothing to the study and/or were obvious such as ‘microalgae’ or ‘article’. The results are shown in two different formats: a bar diagram and a cloudword (Fig. 10). In both cases only the keywords that appear in at least 1000 articles are represented. These mainly include terms related to the microalgae cultivation applications such as ‘biomass’ ‘biofuel’ or ‘lipids’. Although others also appear that are related to the studied organism such as ‘*Chlorella*’ or ‘Green Alga’ and some related to the methodology such as ‘bioreactor’. Out of all of them ‘biomass’ and ‘biofuel’ stand out as they appear in almost 20% of publications.

Fig. 11 shows the communities' distribution of all the keywords appearing in at least 150 articles, and the connections established around them. As can be observed, 8 communities appear, each identified by a color. The two main communities are represented by the colors green and red. The green community revolves around the keywords ‘wastewater’ and ‘*Chlorella*’, probably influenced by the importance of research related to wastewater treatment using *C. vulgaris*. The red community is centered on the keywords ‘photosynthesis’, ‘nutrients’, and ‘growth’, influenced by the large number of publications focused on the optimization of microalgae culture conditions.

The seven microalgae genera appearing in the keywords of the studied articles are analyzed individually (Fig. 12). Firstly, the distribution of articles by country has been represented. Next, the different genus were taken as the abscissa axis. Through the analysis of both representations, we verified that the interest for each microalgae is not the same for the countries studied. Hence, one can see that *Chlamydomonas* and *Nannochloropsis* are mostly studied in the USA; *Chlorella* and *Scenedesmus* are studied mainly in China; and *Phaeodactylum* and *Isochrysis*, in Spain. The seventh most present microalgae in the literature, *Spirulina*, is curiously not one of the most studied microalgae in any of the 10 countries with the highest number of publications in this area; it is instead most studied in Brazil.

A keywords analysis of the four countries with the highest scientific production (the USA, China, Spain and France) was also carried out and the results are represented in four cloudwords (Fig. 13). It can be observed how, in the case of the USA, the obtained cloudword is practically identical to the general cloudword (Fig. 10B). The only difference one could highlight is the increase in the size of the keywords ‘photosynthesis’ and ‘nitrogen’. Nevertheless, there are differences in the other

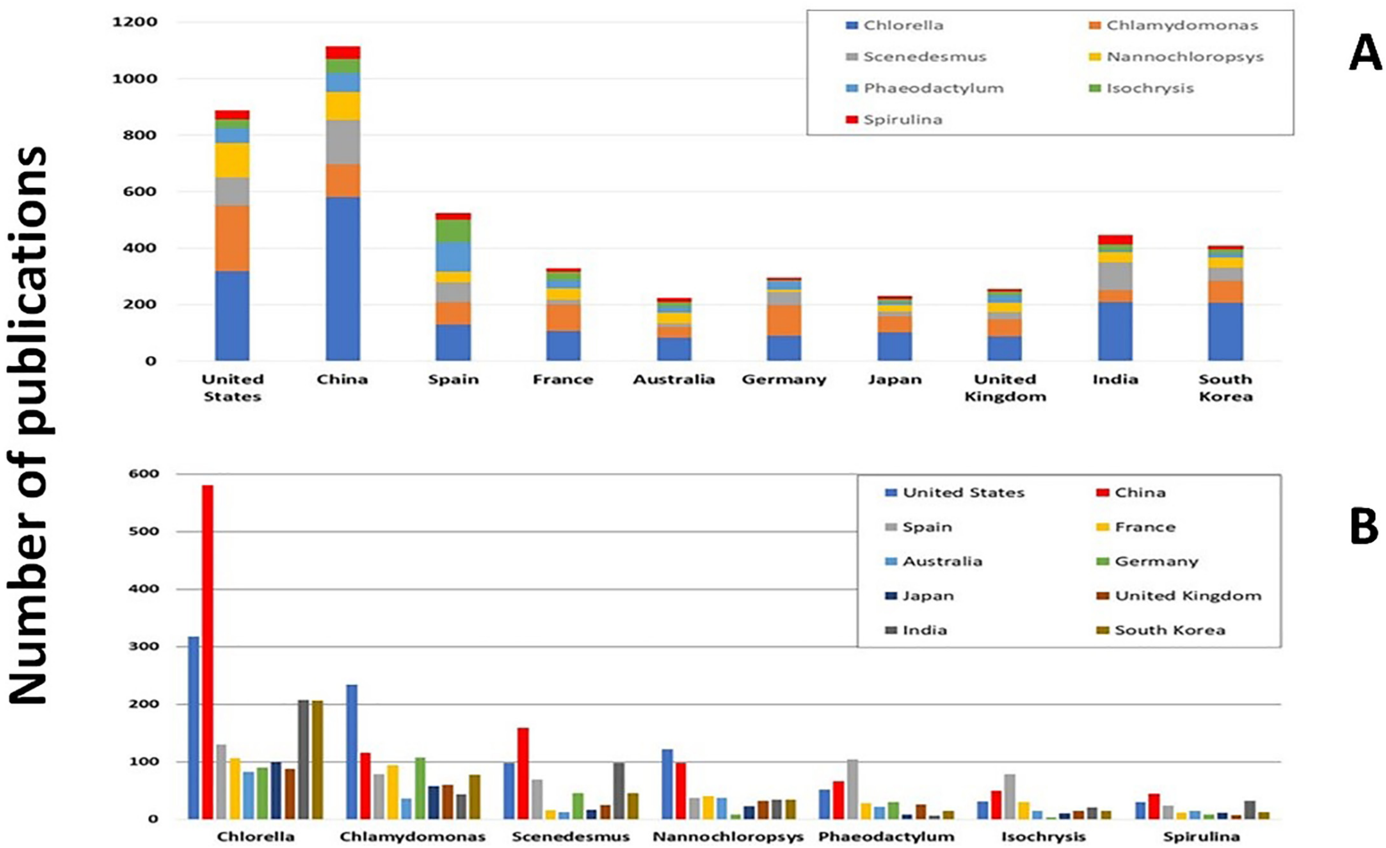

Fig. 12. Representation of the number of publications related to each genus and to each country. A) By country. B) By microalgae.

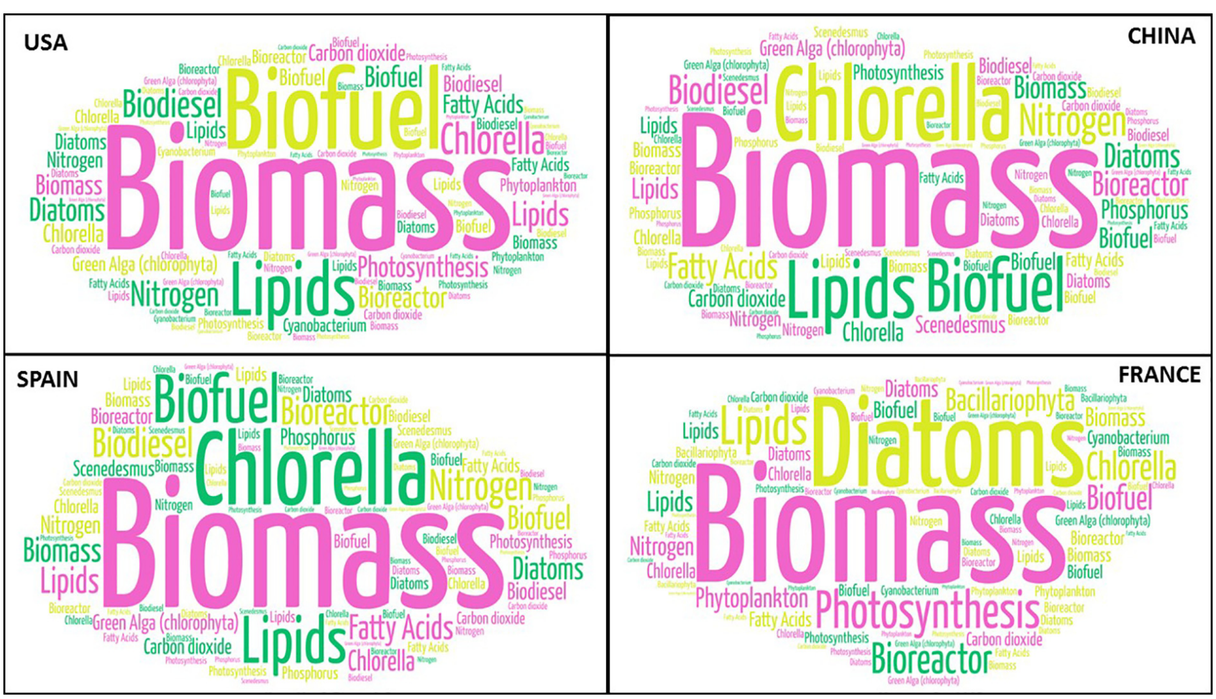

Fig. 13. Cloudword of the four countries with the highest scientific production on microalgae.

three cloudwords. In the case of China, the terms 'cyanobacterium' and 'phytoplankton' disappear, while 'phosphorus' and '*Scenedesmus*' appear. Furthermore, the increase in size of 'nitrogen' and the reduction in size of 'diatoms' is remarkable. On the other hand, 'biodiesel' and 'cyanobacterium' disappear from the cloudword for Spain, with respect to the general graph, while '*Phaeodactylum tricornutum*' and 'wastewater' appear. In addition, the increase in size of 'bioreactor' is emphasized, as is the significant decrease of 'biofuel'. For the last cloudword, that of France, the term 'biodiesel' disappears, while '*bacillariophyta*' appears. 'Photosynthesis', 'diatoms' and 'phytoplankton' increase in size while

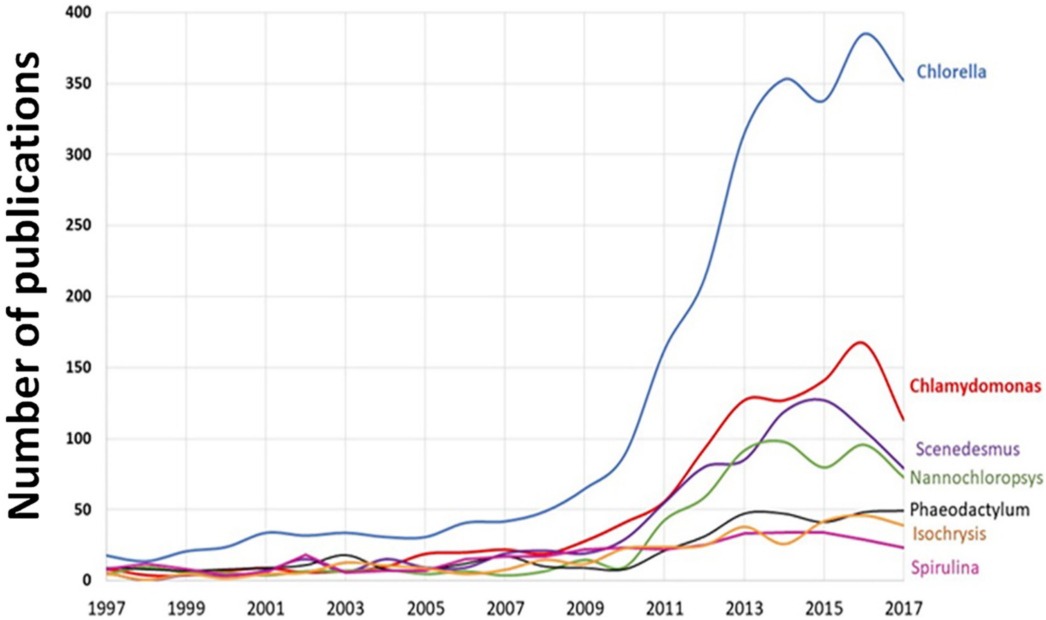

Fig. 14. Time evolution of the publication numbers of the most studied microalgae genus.

'biofuel' and 'fatty acids' decrease.

Finally, we studied the time evolution of the publications for the seven most important microalgae (Fig. 14). This analysis was performed for the last 20 years, 1997–2017, since these are the years for which we have complete data. Prior to 1997, the number of publications was negligible for each species. For *Chlorella*, the number of published articles is 73, while for the other genus it is less than 25. In this study, similar behavior is seen for all microalgae in the 1997 to 2010 period growth was moderate. As of 2010, growth is remarkable, especially for *Chlorella*. The rest of the species are divided into two groups. On the one hand, for *Chlamydomonas*, *Scenedesmus* and *Nannochloropsis*, the takeoff was also considerable although well below *Chlorella*. On the other hand, for *Phaeodactylum*, *Isochrysis* and *Spirulina*, although the number of publications around them also increased, it happened in a very moderate way.

4. Conclusions

Analyzing the number of publications on microalgae, from 1970 to 2017, a great increase in the evolution is observed, which is especially outstanding from the year 2005 onwards. This is consistent with the increase over recent years in the market demand for microalgae-derived products and the great boom in the number of facilities for microalgae cultivation [34]. In this study, in addition to the trend regarding the number of publications, other variables related to scientific production have been studied, such as the types and languages of publications, the major authors and the institutions. Thus, most of the publications are articles (81.45%) and, to a lesser extent, conference papers (6.46%) and reviews (5.88%), and almost all are written in English (95.20%). Most of these articles are published by two sources: *Bioresource Technology* and *Algal Research*. Both published 15.35% of all articles on microalgae in 2017.

The country publishing most on this subject is the United States (3615 publications), followed by China (3005 publications). Next, but far behind, are two European countries, Spain and France (1593 and 1456 articles, respectively). Looking at the institutions that publish the most, it can be seen that, amongst the former, there is no single institution from the USA dominating and appearing in the top list of institutions as would be expected. This is because the institutions that occupy the top positions in the ranking of publications occupy very prominent places within their respective countries in terms of microalgae research, whereas in the United States there is an extensive network of institutions focused on microalgae study, none of which especially stand out above the others.

When the keywords for articles in microalgae publications are studied, it can be seen that the one with the highest presence, 'biomass', is related to the first product of interest obtained from these organisms. The next term with the greatest presence is 'biofuel'. This is consistent with the significant interest aroused by microalgae as a bioenergetic resource; even though, to date, this line has not had all the success that was expected. Other keywords that appear in high ranking positions relate to microalgae applications in the market like 'lipids' or 'fatty acids'.

Observing the strains that are most present in the scientific literature, we can see how the first positions are occupied by those most classically studied, *Chlorella* and *Chlamydomonas*. Nonetheless, we have also been able to verify how interest in a certain strain largely depends on the country where it is studied. For example, in the USA there is more interest in the two strains mentioned above whereas in China, *Scenedesmus* occupies a prominent position; in Spain, the most studied microalgae is *Phaeodactylum* and in Brazil, *Spirulina*. Other strains such as *Dunaliella*, *Euglena*, *Porphyridium* or *Haematococcus* are not yet widely present in the scientific literature, but it is expected that over the coming years, the number of publications that study them will increase considerably [35,36].

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Authors' contribution

Authors mutually agree to submit this paper for publication in Algal Research. Jose Antonio Garrido Cárdenas perform the bibliographic revision and analysis of data, whereas Francisco Manzano Agugliaro and F. Gabriel Acien were responsible for the on depth analysis of data and discussion of more relevant phenomena. All of them, in collaboration with E. Molina Grima participated in the preparation and revision of the manuscript.

Conflict of interest statement

The authors declare that there is no potential financial or other interests that could be perceived to influence the outcomes of the research.

Statement of informed consent, human/animal rights

No conflicts, informed consent, human or animal rights applicable.

Declaration of authors' agreement

The authors mutually agree to submit this paper for publication in Algal Research. No other persons have been involved in this work.

References

[1] P. Spolaore, C. Joannis-Cassan, E. Duran, A. Isambert, Commercial applications of microalgae, J. Biosci. Bioeng. 101 (2006) 87–96.
[2] J.S. Burlew, Algal Culture From Laboratory to Pilot Plant, Carnegie Institution, Washington, USA, 1953, pp. 235–281.
[3] C.G. Golueke, W.J. Oswald, Power from solar energy—via algae-produced methane, Sol. Energy 7 (1963) 86–92, https://doi.org/10.1016/0038-092X(63)90033-1.
[4] S.J. Pirt, Y.K. Lee, M.R. Walach, M. Watts Pirt, H.H.M. Balyuzi, M.J. Bazin, A tubular bioreactor for photosynthetic production of biomass from carbon dioxide: design and performance, J. Chem. Technol. Biotechnol. 33B (1983) 35–58, https://doi.org/10.1002/jctb.280330105.
[5] A. Richmond, Microalgal biotechnology at the turn of the millennium: a personal view, J. Appl. Phycol. 12 (2000) 441–451.
[6] S. Leu, S. Boussiba, Advances in the production of high-value products by microalgae, Ind. Biotechnol. 10 (2014) 169–183, https://doi.org/10.1089/ind.2013.0039.
[7] M.A. Borowitzka, High-value products from microalgae-their development and commercialisation, J. Appl. Phycol. 25 (2013) 743–756, https://doi.org/10.1007/s10811-013-9983-9.
[8] A. Muller-Feuga, The role of microalgae in aquaculture: situation and trends, J. Appl. Phycol. 12 (2000) 527–534, https://doi.org/10.1023/A:1008106304417.
[9] D. Han, Y. Li, Q. Hu, Astaxanthin in Microalgae: Pathways, Functions and Biotechnological Implications, 28 (2013), pp. 131–147.
[10] Y. Dautor, P. Úbeda-Mínguez, T. Chileh, F. García-Maroto, D.L. Alonso, Development of genetic transformation methodologies for an industrially-promising microalga: *Scenedesmus almeriensis*, Biotechnol. Lett. 36 (2014) 2551–2558, https://doi.org/10.1007/s10529-014-1641-z.
[11] M. Guo, X. Bian, X. Wu, M. Wu, *Agrobacterium*-mediated genetic transformation: history and progress, Genet. Transform. (2010) 328, https://doi.org/10.5772/22026.
[12] F.G. Acién Fernández, J.M. Fernández Sevilla, E. Molina Grima, Photobioreactors for the production of microalgae, Rev. Environ. Sci. Biotechnol. 12 (2013) 131–151.
[13] C. Posten, Design principles of photo-bioreactors for cultivation of microalgae, Eng. Life Sci. 9 (2009) 165–177, https://doi.org/10.1002/elsc.200900003.
[14] E. Molina Grima, J.M. Fernández Sevilla, J.A. Sánchez Pérez, F. García Camacho, E. Molina-Grima, J.M.F. Sevilla, J.A.S. Pérez, F.G. Camacho, A study on simultaneous photolimitation and photoinhibition in dense microalgal cultures taking into account incident and averaged irradiances, J. Biotechnol. 45 (1996) 59–69, https://doi.org/10.1016/0168-1656(95)00144-1.
[15] F.G. Acien, J.M. Fernandez, E. Molina-Grima, Economics of microalgae biomass production, Biofuels From Algae, 2013, pp. 313–325, , https://doi.org/10.1016/B978-0-444-59558-4.00014-0.
[16] I. de Godos, J.L. Mendoza, F.G. Acién, E. Molina, C.J. Banks, S. Heaven, F. Rogalla, Evaluation of carbon dioxide mass transfer in raceway reactors for microalgae culture using flue gases, Bioresour. Technol. 153 (2014) 307–314, https://doi.org/10.1016/j.biortech.2013.11.087.
[17] I. Fernández, F.G. Acién, J.M. Fernández, J.L. Guzmán, J.J. Magán, M. Berenguel, Dynamic model of microalgal production in tubular photobioreactors, Bioresour. Technol. 126 (2012) 172–181, https://doi.org/10.1016/j.biortech.2012.08.087.
[18] J.L. Mendoza, M.R. Granados, I. de Godos, F.G. Acién, E. Molina, S. Heaven, C.J. Banks, Oxygen transfer and evolution in microalgal culture in open raceways, Bioresour. Technol. 137 (2013) 188–195, https://doi.org/10.1016/j.biortech.2013.03.127.
[19] E.M.M. Grima, F.G.A. Fernández, A.R. Medina, F.G. Acién Fernández, A. Robles Medina, Downstream Processing of Cell Mass and Products, (2013).
[20] F.G. Acién, J.M. Fernández, J.J. Magán, E. Molina, Production cost of a real microalgae production plant and strategies to reduce it, Biotechnol. Adv. 30 (2012) 1344–1353.
[21] N.-H. Norsker, M.J. Barbosa, M.H. Vermuë, R.H. Wijffels, Microalgal production—a close look at the economics, Biotechnol. Adv. 29 (2011) 24–27.
[22] Y. Chisti, Biodiesel from microalgae, Biotechnol. Adv. 25 (2007) 294–306.
[23] R.H. Wijffels, M.J. Barbosa, An outlook on microalgal biofuels, Science 329 (2010) 796–799, https://doi.org/10.1126/science.1189003.
[24] L. Rodolfi, G.C. Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, M.R. Tredici, Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor, Biotechnol. Bioeng. 102 (2009) 100–112, https://doi.org/10.1002/bit.22033.
[25] J. Benemann, Microalgae for biofuels and animal feeds, Energies 6 (2013) 5869–5886.
[26] M. Vigani, C. Parisi, E. Rodríguez-Cerezo, M.J. Barbosa, L. Sijtsma, M. Ploeg, C. Enzing, Food and feed products from micro-algae: market opportunities and challenges for the EU, Trends Food Sci. Technol. 42 (2015) 81–92.
[27] M.J. Cobo, M.A. Martínez, M. Gutiérrez-Salcedo, H. Fujita, E. Herrera-Viedma, 25 years at knowledge-based systems: a bibliometric analysis, Knowl.-Based Syst. 80 (2015) 3–13, https://doi.org/10.1016/j.knosys.2014.12.035.
[28] M.A. Martínez, M.J. Cobo, M. Herrera, E. Herrera-Viedma, Analyzing the scientific evolution of social work using science mapping, Res. Soc. Work. Pract. 25 (2015) 257–277, https://doi.org/10.1177/1049731514522101.
[29] O. Ellegaard, J.A. Wallin, The bibliometric analysis of scholarly production: how great is the impact? Scientometrics 105 (2015) 1809–1831, https://doi.org/10.1007/s11192-015-1645-z.
[30] J.A. Garrido-Cardenas, F. Manzano-Agugliaro, The metagenomics worldwide research, Curr. Genet. (2017), https://doi.org/10.1007/s00294-017-0693-8.
[31] F. Juliani, O.J. de Oliveira, State of research on public service management: identifying scientific gaps from a bibliometric study, Int. J. Inf. Manag. 36 (2016) 1033–1041, https://doi.org/10.1016/j.ijinfomgt.2016.07.003.
[32] F.G. Montoya, M.G. Montoya, J. Gómez, F. Manzano-Agugliaro, E. Alameda-Hernández, The research on energy in Spain: a scientometric approach, Renew. Sust. Energ. Rev. 29 (2014) 173–183.
[33] F.G. Montoya, R. Baños, J.E. Meroño, F. Manzano-Agugliaro, The research of water use in Spain, J. Clean. Prod. 112 (2016) 4719–4732, https://doi.org/10.1016/j.jclepro.2015.06.042.
[34] E. Forján, F. Navarro, M. Cuaresma, I. Vaquero, M.C. Ruíz-Domínguez, Ž. Gojkovic, M. Vázquez, M. Márquez, B. Mogedas, E. Bermejo, S. Girlich, M.J. Domínguez, C. Vílchez, J.M. Vega, I. Garbayo, Microalgae: fast-growth sustainable green factories, Crit. Rev. Environ. Sci. Technol. 45 (2014) 1705–1755, https://doi.org/10.1080/10643389.2014.966426.
[35] S.R. Medipally, F.M. Yusoff, S. Banerjee, M. Shariff, Microalgae as sustainable renewable energy feedstock for biofuel production, Biomed. Res. Int. 2015 (2015).
[36] W. Yee, Microalgae from the Selenastraceae as emerging candidates for biodiesel production: a mini review, World J. Microbiol. Biotechnol. 32 (2016) 1–11.