Algal Research 35 (2018) 50–60

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Review article

Microalgae research worldwide

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ARTICLE INFO

Keywords:
Bibliometric
Biotechnology
Publications
Researchers
Journals

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].

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https://doi.org/10.1016/j.algal.2018.08.005
Received 2 May 2018; Received in revised form 4 August 2018; Accepted 6 August 2018

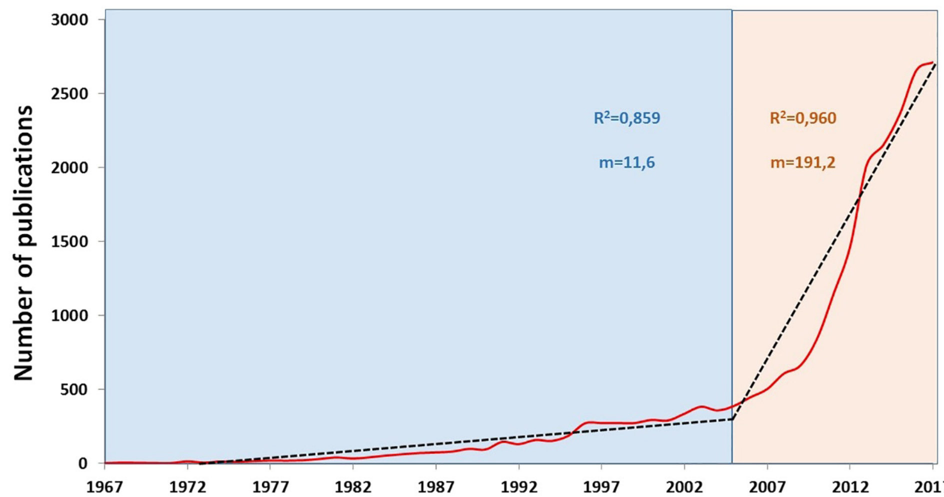

Fig. 1. Trend in the number of publications from 1970 to 2017.

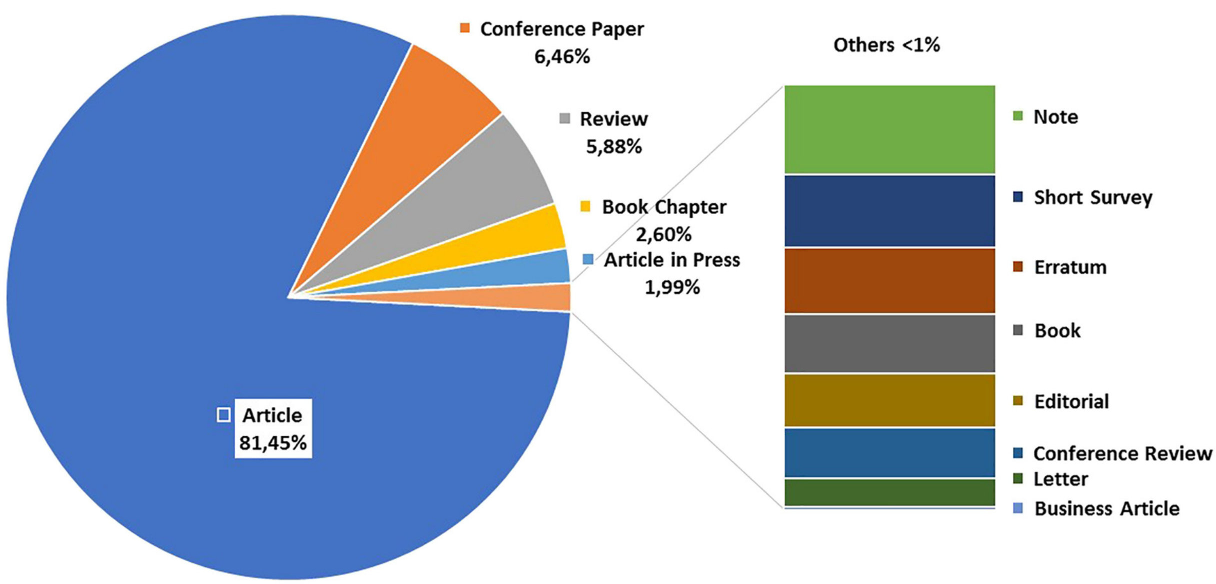

Fig. 2. Distribution of document types for microalgae.

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