Trends in Food Science & Technology 69 (2017) 157–171

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: http://www.journals.elsevier.com/trends-in-food-science-and-technology

Review

Spirulina – From growth to nutritional product: A review

Ruma Arora Soni [a], K. Sudhakar [a, c, *], R.S. Rana [b]

[a] Energy Centre, Maulana Azad National Institute of Technology, Bhopal, M.P, India
[b] Department of Mechanical Engineering, Maulana Azad National Institute of Technology, Bhopal, M.P, India
[c] Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pahang, Malaysia

ARTICLE INFO

Article history:
Received 12 April 2017
Received in revised form
18 June 2017
Accepted 25 September 2017
Available online 28 September 2017

Keywords:
Spirulina
Pharmaceutical
Nutritional use
Dietary supplement
Open pond
PBR

ABSTRACT

Background: *Spirulina* is multicellular and filamentous cyanobacteria that have achieved a considerable popularity in the health sector, food industry and aquacultures. It develops and grows in water, can be harvested and processed easily. It has very high content of macro and micronutrients, essential amino acids, proteins, lipids, vitamins, minerals and anti-oxidants. *Spirulina* is considered as a complete food supplement to fight against malnutritional deficiencies in developing countries. *Spirulina* is deemed safe for human consumption as evident by its long history of food use and latest scientific findings. In recent years, *Spirulina* has gathered enormous attention from research fraternity as well as industries as a flourishing source of nutraceutical and pharmaceuticals.

Scope and approach: The primary objective of this paper is to review the utilization of *Spirulina* as a dietary supplement in the food industry. In the present work, the three main area of *Spirulina* research: growth, harvesting and potential application are presented.

Key findings and conclusion: The important growth parameters have been studied to enhance *Spirulina* biomass productivity qualitatively and quantitatively. This review provides useful information on commercially viable technology for *Spirulina* cultivation. Mass cultivation and Innovative formulations are further needed to fortify conventional foods with *Spirulina* based protein system.

1. Introduction

Algae are photosynthetic organisms that convert light energy from the sun into the chemical energy by the process of photosynthesis. Algae possess simple reproductive structure. The biomass of algae contains various compounds with diversified structures and functions. Algal biotechnology is divided into microalgae, macroalgae and cyanobacteria with its unique specificity (Becker, 2007). Sometimes cyanobacteria are also included in microalgae. Microalgae classification includes prokaryotic and eukaryotic unicellular and multicellular. Microscopic are microalgae, Cyanobacteria, are prokaryotic. The *Spirulina* is Earth's oldest living plant approximately 3.6 billion years ago and a first photosynthetic life form that has created our oxygen atmosphere so all life could evolve. Blue-green algae are the evolutionary bridge between green plants and bacteria. At present the main directions in microalgal biotechnology are biofuels, agricultural biostimulants for crop plants, waste water treatment etc. Microalgal biotechnologies refer to the production of different products as phycocyanin, carotenoids, fatty acids and lipids for application in health food, cosmetics, food supplements, pharmaceuticals and fuel production. Microalgal groups of major importance are chlorophyte, bacillariophytes, while macroalgae are harvested from natural habitats. Algae that is currently cultivated for its maximum protein content is the cyanobacterium species *Athrospira*, which is commonly known as *Spirulina*.

Spirulina was first discovered by Spanish Scientist Hernando Cortez and Conquistadors in 1519. Cortez observed that Spirulina was eaten at the tables of the Aztecs during his visit in Lake Texcoco in the Valley of Mexico. Pierre Dangeard discovered the health benefits of *Spirulina* who observed that flamingos were surviving by consuming blue-green algae. Botanist Jean Leonard supported the findings of Dangeard and people soon started to commercialize Spirulina to reap its benefits (Ugwu, Aoyagi, & Uchiyama, 2008). The first Spirulina processing plant, Sosa Texcoco, was set up in 1969 by the French.

Spirulina is the most nutritious, concentrated food that is known

* Corresponding author. Energy Centre, Maulana Azad National Institute of Technology, Bhopal, M.P, India.
E-mail addresses: rumaarora14@gmail.com (R.A. Soni), sudhakar.i@manit.ac.in (K. Sudhakar).

https://doi.org/10.1016/j.tifs.2017.09.010
0924-2244/

Nomenclature

(P_X)	Cell productivity
(T_C)	Cultivation time
Γ	Productivity of the system
μ	Specific growth rate
x	Biomass concentration
(X_m- X_i)	Cell concentration
N_0	Initial population size
t	Amount of time that has past
N_t	Population size at time
G	Generation time
N.S	Not Specified

to mankind containing antioxidants, phytonutrients, probiotics, and nutraceuticals. *Spirulina* is fast emerging as a complete answer to the varied demands due to its imposing nutrient composition which can be used for therapeutic uses. The United Nations world at food conference declared that *Spirulina* as the best food for future, and it is gaining popularity nowadays (Pulz & Gross, 2004). World Health Organization has described *spirulina* as Mankind's best health product. According to UNESCO, *spirulina* is most ideal food for tomorrow. According to NASA and European Space Agency, it is one of the primary foods that can be cultivated in long-term space missions in space. FDA validated it as “One of the best protein source”. Intergovernmental institution permitted for the use of Micro-algae *Spirulina* against Malnutrition (IIMSAM).

The two most important species of *Spirulina* are *Spirulina maxima* and *Spirulina platensis.* It has a considerable high content of micro and macronutrients. Its dry weight chemical composition includes 60–70% proteins, carbohydrates, vitamins like provitamin A, vitamin C, vitamin E, minerals such as iron, calcium, chromium, copper, magnesium, manganese, phosphorus, potassium, sodium and zinc. Essential fatty acids γ-linolenic acid (GLA), pigments like chlorophyll *a*, phycocyanin and carotenes are also present. *Spirulina* is also used in cosmetics, medicines and waste water treatment. Its cell wall consists of polysaccharides that have a digestibility of 86%, and can be easily absorbed by the human body (Sjors & Alessandro, 2010). These microalgae contain chlorophyll *a*, like higher plants; therefore it is classified as microalgae according to botanists belonging to *Cyanophyceae* class; and bacterium due to its prokaryotic structure according to bacteriologists (Koru, 2009; Sudhakar & Premalatha, 2015).

Spirulina is a planktonic photosynthetic cyanobacterium that forms huge populations in tropical as well as subtropical bodies of water which contain a high amount of salts such as carbonate and bicarbonate with alkaline pH 9.5(Sjors & Alessandro, 2010; Habib, Parvin, Huntington, & Hasan, 2008, pp. 1–41). Generally, microalgae have higher growth rates, higher CO_2 fixation efficiency and larger quantities of high-value products, such as dietary supplements for human along with animals (Anupama, 2000; Zeng, Danquah, Chen, & Lu, 2011). Cost effectiveness and composition of cultivation media along with growth rate needs to be managed properly for commercially viable production. From ancient times different media have been used for cultivation of *Spirulina* and monitoring its growth rate i.e. Zarrouk's media (Zarrouk, 1966), Rao's media, CFTIR media, OFERR media, revised media (Raoof, Kaushika, & &Prasanna, 2006).

Past few decades have seen considerable progress in *spirulina* cultivation for nutritional use however there is no substantial argument on the nutritional productivities, best cultivation method, and ideal growth conditions. This review addresses these issues based on prior publications and the author's prior work in the large scale cultivation of *spirulina* for nutritional products. The article starts with the illustration of *spirulina* growth chain from identifying suitable strain to the final product.

The present study focuses on growth rate, productivity, growth parameters, different cultivation systems (outdoor and indoor systems), harvesting and drying techniques of *Spirulina.* This review focuses on following aspects:

- Strain selection and cultivation of *Spirulina.*
- Optimum parameters for growth of *Spirulina.*
- Harvesting and drying techniques of *Spirulina.*
- Commercial applications of *Spirulina* as pharmaceutical and nutraceuticals product.

2. Review of growth system

Cultivation of algae can be done in open systems like ponds, lakes or lagoons or in a closed system (Singh and Sharma 2012). Presently, two major technologies are being considered for the cultivation of Spirulina: closed photobioreactors (PBR) and open ponds. Both approaches are used commercially to produce high-value products.

2.1. Open pond system

Cultivation of algae in open ponds has been extensively studied (Vardaka, Kormas, Katsiapi, Genitsaris, & Moustaka-Gouni, 2016; Zhang et al., 2015; Madhu, Satyanarayana, Kalpana, & Bindiya, 2015; Vega-Estrada, Montes-Horcasitas., Dominígues-Bocanegra, & Cañizares-Villanueva, 2005). Open ponds can be categorized into natural waters as lakes, lagoons, ponds and artificial ponds or containers. The most commonly used systems are shallow big ponds, circular ponds, tanks and raceway ponds. Open systems are easier in construction and operation, results in low production and operating cost (Ugwu et al., 2008). The major drawback in open ponds includes poor light utilization by the cells, evaporative losses, diffusion of carbon dioxide to the atmosphere, and requirement of large acres of land. Also, due to inefficient aeration in open cultivation systems, their mass transfer rates are very poor resulting in less biomass productivity. The growth also depends on location, season, temperature, pH level, nutrient and carbon - dioxide supply (Cuaresma, Janseen, & VilchezWijffels, 2011). The other major drawback of open pond system is the contamination by fauna and other fast growing heterotrophs. To expel the problems associated with an open system, researchers have tried for closed systems (Singh and Sharma 2012).

Table 1 summarizes the advantages and limitations of open ponds, photobioreactors and hybrid system. Large quantities of algae can be grown but they are difficult to grow outdoor as they easily get contaminated. This can be rectified by growing algae in greenhouses, which protect them from foreign particles in the air. The optimally designed algae greenhouse and controlled environment systems can increase productivity 10 fold compared to outdoor growth. Construction of greenhouse includes design and optimizing for improved biomass yield. Controlled environment algae facilities are gaining momentum due to improved yields and reduced contamination. The internal systems to control the internal humidity, temperature, and carbon dioxide through the use of fans, vents, evaporative cooling, and climate zoning is done (Sierra, Acien, Fernandez, Garcıa, & GonzalezMolina, 2008). pH, nutrients, and bacteria are regulated in the water system through fertigation, oxygenation and also sterilization. Integrating the climatic conditions, water, and nutrient systems with simulation allows us to