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Research review paper

Microalgal lipids biochemistry and biotechnological perspectives

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ABSTRACT

In the last few years, there has been an intense interest in using microalgal lipids in food, chemical and pharmaceutical industries and cosmetology, while a noteworthy research has been performed focusing on all aspects of microalgal lipid production. This includes basic research on the pathways of solar energy conversion and on lipid biosynthesis and catabolism, and applied research dealing with the various biological and technical bottlenecks of the lipid production process. In here, we review the current knowledge in microalgal lipids with respect to their metabolism and various biotechnological applications, and we discuss potential future perspectives.

The committing step in fatty acid biosynthesis is the carboxylation of acetyl-CoA to form malonyl-CoA that is then introduced in the fatty acid synthesis cycle leading to the formation of palmitic and stearic acids. Oleic acid may also be synthesized after stearic acid desaturation while further conversions of the fatty acids (i.e. desaturations, elongations) occur after their esterification with structural lipids of both plastids and the endoplasmic reticulum. The aliphatic chains are also used as building blocks for structuring storage acylglycerols via the Kennedy pathway. Current research, aiming to enhance lipogenesis in the microalgal cell, is focusing on over-expressing key-enzymes involved in the earlier steps of the pathway of fatty acid synthesis. A complementary plan would be the repression of lipid catabolism by down-regulating acylglycerol hydrolysis and/or β-oxidation. The tendency of oleaginous microalgae to synthesize, apart from lipids, significant amounts of other energy-rich compounds such as sugars, in processes competitive to lipogenesis, deserves attention since the lipid yield may be considerably increased by blocking competitive metabolic pathways.

The majority of microalgal production occurs in outdoor cultivation and for this reason biotechnological applications face some difficulties. Therefore, algal production systems need to be improved and harvesting systems need to be more effective in order for their industrial applications to become more competitive and economically viable. Besides, a reduction of the production cost of microalgal lipids can be achieved by combining lipid production with other commercial applications. The combined production of bioactive products and lipids, when possible, can support the commercial viability of both processes. Hydrophobic compounds can be extracted simultaneously with lipids and then purified, while hydrophilic compounds such as proteins and sugars may be extracted from the defatted biomass. The microalgae also have applications in environmental biotechnology since they can be used for bioremediation of wastewater and to monitor environmental toxicants. Algal biomass produced during wastewater treatment may be further valorized in the biofuel manufacture.

It is anticipated that the high microalgal lipid potential will force research towards finding effective ways to manipulate biochemical pathways involved in lipid biosynthesis and towards cost effective algal cultivation and harvesting systems, as well.

Contents

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Introduction

The microalgae are photosynthetic microorganisms that play a key role in the natural ecosystems supplying organic matter and specific molecules, such as polyunsaturated fatty acids (PUFAs), to many higher organisms. Microalgae applications range from human and animal nutrition to cosmetics and the production of high value molecules.

The systematic development of microalgal applications started in the 20th century. Several species are currently cultivated in large scale, in artificial or natural ponds and rarely in photobioreactors (PBRs), producing up to some tons of biomass and/or various metabolites per year. Algal biomass is rich in PUFAs, minerals (e.g. Na, K, Ca, Mg, Fe, Zn and trace minerals) and vitamins, such as riboflavin, thiamin, carotene and folic acid and so on (Becker, 2004; García-Garibay et al., 2003; Samarakoona and Jeona, 2012). The microalgal biomass, especially that produced by the species *Dunaliella*, *Arthrospira* (*Spirulina*, cyanobacterium) and *Chlorella*, is already marketed in various forms designed for human nutrition or is incorporated into foods and beverages (Liang et al., 2004; Yamaguchi, 1997), as it is considered a healthy nutritional supplement (Apt and Behrens, 1999; Borowitzka, 1999; Jensen et al., 2001; Priyadarshani and Rath, 2012; Soletto et al., 2005). Similarly, the consumption of even small amounts of microalgal biomass can positively affect the physiology of animals by improving immune response, diseases' resistance, antiviral and antibacterial protection, improved gut function, probiotic colonization stimulation, as well as enhanced feed conversion, reproductive performance and weight control (Harel and Clayton, 2004). Although the quality of algal proteins lags behind that of animal proteins, it is superior to that of common plants (Barrow and Shahidi, 2008; Becker, 2004; Kay and Barton, 1991; Samarakoona and Jeona, 2012; Sydney et al., 2010; Um and Kim, 2009). Particular algal peptides, such as taurine, are of great nutritional and pharmaceutical interest (Houstan, 2005), while glycoproteins (lectins), extracted by marine algae, are considered a type of interesting proteins for biochemical and clinical research, and can be isolated with their carbohydrate moiety (Silva et al., 2010).

Some species contain considerable amounts of pigments that are used in cosmetics and as natural coloring agents. Many industrial production plants are established in China, Australia and USA (Brown et al., 1997; García-González et al., 2005; León et al., 2003) dealing with beta-carotene production (e.g. from *Dunaliella salina*) that is used as a food coloring (Metting, 1996). Other pigments such as phycobiliproteins have been extracted from various marine algae including *Porphyridium cruentum* and *Synechococcus* spp. (Viskari and Colyer, 2003).

Although the majority of applications concern biomass production destined for animal or human consumption — in fact, 30% of the current world algal production is sold for animal feed applications (Becker, 2004) — there has been an increased interest in the use of microalgal lipids in numerous commercial applications, such as in food, chemical and pharmaceutical industries and cosmetology. Indicative of the high interest in microalgal lipids is the noteworthy research that has been performed in the last decade on all aspects concerning microalgal lipid production. These include fundamental research on the mechanisms used for light energy conversion and on lipid biosynthesis and catabolism, as well as biotechnological research dealing with the various technical bottlenecks of the lipid production process. In the current review article the up-to-date level of knowledge in lipid biosynthesis and turnover in microalgae and the various biotechnological applications and future perspectives of microalgal lipids are comprehensively presented and discussed. Taking into consideration the recent techno-economic analyses concluding that the algal lipid content is the most critical factor affecting the viability of large-scale applications, especially those related to biodiesel, the current research efforts aimed to reinforce algal liposynthetic machinery using genetic engineering are also discussed.

Microalgal lipids in the forefront of lipid biotechnology

Several microalgal species are able to accumulate appreciable lipid quantities, and therefore are characterized as oleaginous. Lipid content in microalgae can reach up to 80% in dry biomass, but even in these cases the lipid productivity is actually low. In widespread species belonging to the genera of *Porphyridium*, *Dunaliella*, *Isochrysis*, *Nannochloropsis*, *Tetraselmis*, *Phaeodactylum*, *Chlorella* and *Schizochytrium*, lipid content varies between 20 and 50%. However, higher lipid accumulation can be reached by varying the culture conditions. Factors such as temperature, irradiance and, mostly, nutrient availability have been shown to affect lipid content and composition in algal cells.

The interest for algal lipid arises mainly from the fact that these organisms are able to synthesize considerable quantities of PUFAs that either reach humans via the food chain or are used as food supplements (Fig. 1). Indeed microalgae are the primary source of PUFAs having nutritional and pharmaceutical interest (Doughman et al., 2007; Kyle, 2001). Although fish are also a source of PUFAs, these organisms usually obtain their PUFAs via bioaccumulation through the food chain (Benemann et al., 1987). Furthermore, fish PUFA production depends on fish quality and sufficiency while that of algae does not.

Several microalgae are able to synthesize omega-3-long chain PUFAs, at levels over 20% of their total lipids. In algal cell PUFAs are esterified with an alcohol, usually glycerol, generating triacylglycerols (TAGs) or polar lipids (i.e. phospholipids, glycolipids) of exceptional structure regulating membranes fluidity and function. Depending on the strain, lipid industrial production can be combined with the production of other metabolic products of high value, such as beta-carotene and astaxanthine. The main drawback in using microalgae to produce PUFA rich lipid in large scale is the low lipid content in algal cell and the low biomass density in the reactor, usually not exceeding 400–600 mg/L under industrial culture conditions, which increases considerably the harvesting cost.

Alternatively, microalgal lipids represent an attractive source of oil, suitable as feedstock for biodiesel production. Actually, microalgae offer a number of advantages from an industrial perspective. These