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Review article

Microalgae as versatile cellular factories for valued products

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ABSTRACT

As major part of the phytoplankton, microalgae are pivotal for the global food chain. Their exceptional capacity for CO_2-fixation illustrates their indispensable significance to sustain earth's ecosystems. Further, they play a still underestimated role in eliminating contaminants from various environments. In addition to ecological benefit, many microalgal species exhibit high nutritional value and, at the same time, generate valued bio-products: Pigments, lipids, bioactive compounds, certain polysaccharides, bio-hydrogen and even biopolyesters with plastic-like properties have the potential for successful market penetration.

Three substantial pigment groups, namely chlorophylls, carotenoids, and phycobilins, are essential for light harvesting and CO_2 fixation. Those pigments will most likely undergo quick commercial success in “functional food”, cosmetics, aquaculture, pharmaceuticals, or food technology.

Due to often high contents of polyunsaturated fatty acids essential for human metabolism, microalgal oils can be commercialized as health food and in the pharmaceutical and therapeutic field, creating much higher value than by converting them to biofuel.

Finally, algal biomass remaining as residue after product recovery can be used as forage, biogas feedstock or biofertilizer. This utilization is needed for balancing the material- and energy cycles of the entire process. Thus, technology platforms following the principles of bio-refineries shall be established to enable the design of sustainable and economically feasible production of marketable microalgal products.

Contents

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1. Introduction

1.1. General aspects

Microalgae constitute promising bio-catalysts to be implemented in the increasing field of "White Biotechnology". This is valid both for the production of food, feed, fine chemicals, and diverse "green energy carriers" [66,84,115].

Biologically, these unicellular microbes form a broad polyphyletic group with the mutual capability of photosynthetic fixation of CO_2. This results in the generation of various algal cell components, energy and molecular oxygen [112]. The terminus "microalgae" comprises eukaryotic and, if also including the cyanobacterial representatives (Cyanophyta; for historic reasons often also referred to as "blue-green algae"), prokaryotic microbial species [25,54]. To underline their significance for the ecosphere, one should consider the numerous successful studies describing microalgal fixation of atmospheric CO_2, aiming at elevating prevailing ecological concerns such as the greenhouse effect and global warming [56,66,111].

1.2. The broad range of microalgal products

1.2.1. High-prized products

In addition to the utilization of microalgal biomass rich in proteins and minerals for food and feed purposes, there are beneficial special compounds produced by these organisms, such as pigments, enzymes, sugars, lipids with valued fatty acids, sterols, and vitamins (*inter alia* β-carotene, thiamin, riboflavin, niacin, pantothenic acid, pyridoxine, biotin, folic acid). Additionally, the generation of other scarce bioactive compounds, in particular such displaying immune response, anti-cancer, anti-inflammatory and antibiotic activity, is reported [1,75,83]. Therefore, algae can act as chemical platform for cosmetic purposes (e.g. coloring pigments and especially anti-aging skin supplements: extracts from *Chlorella vulgaris* are reported to support collagen repair mechanisms), pharmaceutical and therapeutic applications [24], food technology, and for production of "green energy carriers" like biogas [25], biodiesel [30,31], bio-hydrogen [32], and bioethanol [21].

The exploitation of microalgae for special metabolites is highly attractive because these frequently display exceptionally high market values. As the best investigated genera for production of valued microalgal products, the chlorophyceae *Haematococcus* and *Dunaliella* shall be highlighted as powerful pigment factories, and *Botryococcus braunii* as species with outstanding capacity for lipid accumulation.

Grace to the microalgal cell components discussed before, these organisms are considered as perfect candidates for contemporary fashionable "health food" or "functional food". Indeed, nowadays the market for "functional food" by far surpasses all other uses of microalgae. As example, already in 1997 [57], 2400 t of microalgal biomass was commercialized per year for "health food" purposes just in Japan with a clear upwards trend globally [89].

Apart from microalgal lipids and pigments, special carbohydrates produced by these organisms are of increasing interest due to their potential therapeutic application. Here, ß-1,3-glucan, a natural soluble fiber active as immune-stimulator, antioxidant and reducer of blood cholesterol has to be mentioned, which is accessible from the cultivation of *Chlorella* strains [102]. In addition to the therapeutic use, this carbohydrate can be implemented in food and beverage manufacturing, mainly as fat substitute for texturizing. It is possible to add ß-1,3-glucan to novel food products such as functional beverage, functional bread, ready-to-serve soups, functional snack foods and a variety of sauces, creamers, bakery products, and additional food products [6,76]. Further, sulfated polysaccharides produced by microalgae can be applied in anti-adhesive therapies against bacterial infections both in cold- and warm-blooded animals [9]. It has to be emphasized that ß-1,3-glucan displays a considerably higher market value if compared with other algal carbohydrates that are of importance for technical applications, such as the gelling or thickening compound agar (produced by macroalgae belonging to the *Rhodophyta group*), alginates, cellulose, or carrageenan that is used as emulsifier and stabilizer in various food products. Carrageenan, also known as food-additive E407, can similarly be implemented for pharmaceutical applications. Comprehensive overviews about the use of such texture forming substances are provided by a book edited by Nussinovitch [72]. As detailed later, the polysaccharide starch is also accessible as storage material of various algal species and can be anaerobically converted to bioethanol [21].

1.2.2. Dependence of product formation on cultivation conditions

Only since the last few decades, microalgal cultivation switches from "wild" techniques of farming and harvesting to controlled cultivation strategies in technically advanced systems like racing ponds or photobioreactors [91,107,122]. It is a common feature of microalgae to readily adapt to strongly fluctuating process conditions during biosynthesis, such as salinity, temperature, pH-value and illumination; illumination aspects take light intensity, dark–light cycles and spectral range into account. The extents of biomass production, lipids, pigments, biopolyesters and carbohydrates can vary considerably depending on the conditions the organisms are exposed to [94,98]. This is especially valid in the case of cyanobacterial biopolyester production [1]. Stress provoked by excessive illumination, salinity and temperature is decisive for the change of the pigment pattern during cultivation of an algal species, typically characterized by an increased carotenoid-to-chlorophyll ratio. This is extensively studied in the case of *Dunaliella* sp. [15,20,62]. Therefore, prior to the selection of the appropriate production parameters, the decision has to be made as the case arises to which final product the carbon flux should be directed predominantly. These facts are decisive for the design of an adequate photobioreactor system facilitating high-performance cultivation of microalgae. Such systems should be flexible both for different microalgal species to be cultivated therein, and for different final products.

In many cases, microalgal growth and product formation do not occur simultaneously, e.g. in the case of biopolyesters or oils, where high product formation rates are noticed only after the termination of biomass growth. Here, novel process engineering approaches have to be developed, allowing the independent optimization of both microalgal