Chapter 1
Photosynthetic Pigments in Diatoms

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Abstract In this review, we present current knowledge of diatom photosynthetic pigments, along with some fresh insights into their physicochemical properties, biological role, biosynthetic processes, economic issues, and industrial relevance. Photosynthetic pigments are important bioactive molecules in the food, cosmetics, and pharmaceutical sectors.

Diatoms have distinct pigment composition which is even far different from those found in plants. The pigments present in diatoms are not only responsible for capturing solar energy during the process of photosynthesis, but they also show antioxidant with great role in the photoprotective processes. The chief light-harvesting pigments present in diatoms are chlorophyll a, chlorophyll c, and fucoxanthin; besides them, they also have collection of carotenoids like β-carotene, xanthophylls, diadinoxanthin, violaxanthin, diatoxanthin, and zeaxanthin having photoprotective functions and are generally produced during xanthophyll cycle as reaction intermediates. Commercially, these pigments have great potential application in food additives, pharmaceutics, and cosmetic industries; besides, these pigments are also being used in the field of medicine as remedy and diagnostics. In recent times, these diatoms have emerged as a great source of these bioactive compounds in various industries. A brief overview of the photosynthetic pigment of diatoms and their potential application in commercial field is presented in this review.

Keywords Photosynthetic pigments · Fucoxanthin · Chlorophyll · Diatoms · Biosynthesis pathways · Antioxidant

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P. Srivastava et al. (eds.), *Insights into the World of Diatoms: From Essentials to Applications*, Plant Life and Environment Dynamics,
https://doi.org/10.1007/978-981-19-5920-2_1

1.1 Introduction

Diatoms are photoautotrophic microalgae which may be colonial or unicellular in arrangement, classified as protists of the group of the Bacillariophyta, and initiate various aquatic food chains and serve as important components of coastal and upwelling environments. The phylogenetic origin of diatoms is found to be different from other green micro and macro plants (Armbrust 2009). The diatoms developed from a secondary endocytobiosis of a eukaryotic host and a eukaryotic red alga. They can be found in a variety of environments, including marine, freshwater, and five terrestrial habitats. Various species thrive in typically hostile conditions, such as very acidic ecosystems and thermal water bodies, where temperatures preclude most other living forms from growing. Frustules, which are made of two valves, are exceptionally tough siliceous cell walls found in diatoms (Martin-Jézéquel et al. 2000). Diatoms are present in the environment and in items manufactured using diatomaceous earth, such as cleaning agents, paints, and some types of match heads. Diatom communities are highly sensitive to changes in abiotic conditions and are highly sensitive to environmental change compared to fish and macroinvertebrates (Pandey et al. 2017); hence, they are routinely used for biomonitoring purposes in both lotic and lentic environments. The most prominent unique feature of the photosynthesis apparatus in diatoms is the pigmentation of the light-harvesting apparatus and the thylakoid macrodomain organization. Diatoms are extremely important ecologically since they contribute roughly 20–25% of the world's primary production (Field et al. 1998; Sarthou et al. 2005). When compared to the total quantity fixed by the terrestrial rainforest combined, diatom photosynthetic activity accounts for 40% of marine primary production (Armbrust 2009). Diatoms are characterized by the brown color which originates from a high content of fucoxanthin being bound to "light-harvesting proteins" (LHC) in an equal or even higher ratio than chlorophyll (Chl) a (Gelzinis et al. 2015). The light-harvesting system of diatoms consists of the so-called "fucoxanthin-chlorophyll-protein" (FCP) complexes. Besides fucoxanthin (Fx), which represents the main light-harvesting pigment of diatoms, the xanthophyll cycle pigments "diadinoxanthin" (DD) and "diatoxanthin" (Dt) are additionally present. Different pools of Fx exist within the light-harvesting system, and one of these pools shows light absorption up to 550 nm, thus permitting the use of green light for photosynthesis (Szabo et al. 2010), which cannot be captured by the chlorophylls and other xanthophylls.

These pigments are not only responsible for capturing solar energy to carry out photosynthesis but also play a role in photoprotective processes and display antioxidant activity, all of which contribute to effective biomass and oxygen production. Diatoms are organisms of a distinct pigment composition, substantially different from that present in plants.

Pigments are chemical compounds which provide different colors to the organisms and the parts including flowers, corals, and even animal skin color. They reflect only certain wavelengths of visible light making them appear "colorful." More important than their ability to reflect light, pigments have become widely recognized as a source of unique bioactive compounds having potential use in the industrial, pharmaceutical, and medical fields. They are also rich in bioactive compounds like naviculan having antiviral activity (Lee et al. 2006) and amino acid derivative domoic acid, which have neuroexcitatory effects (Perl et al. 1990), and also contain few nucleotides which show traces of cytotoxic and blood platelet inhibitory activity (Prestegard et al. 2009).There is a wide range of beneficial diatom cell components like lipids and pigments; the amount of which can be influenced by abiotic stressors or genetic changes in metabolic pathways for various applications.

Some unusual pigments have also been reported in few diatoms like *Haslea karadagensis* which have quite different absorption maxima from those of marennine; its similar bioactivity has come to be called marennine-like (Gastineau et al. 2012). Furthermore, the three carotenoids, namely, β-carotene, diadinoxanthin (Ddx), and diatoxanthin (Dtx), are known to play an essential part in photoprotection, while violaxanthin (Vx), antheraxanthin (Ax), and zeaxanthin (Zx) may also be involved. This article focuses on the photosynthetic pigments mentioned above, which are necessary for diatom existence and are widely exploited in numerous sectors.

Although studies in this topic have been conducted for many years, there are still many things that need to be investigated further. The information presented below summarizes current knowledge about photosynthetic pigments found in algae, their biosynthesis processes, cell localization, economic characteristics, and industrial significance.

1.2 Pigment Localization in the Diatom Cell

The diatom cells have either a couple of little chloroplasts or one huge chloroplast (Lavaud 2007). In diatoms, Granal stacking is missing, for example, the thylakoid layers do not show distinction into Granal and stromal lamellae (Gibbs 1970) and contains the colors answerable for the retention of light for photosynthesis. These thylakoid films are organized into gatherings of three approximately stacked lamellae which range through the entire length of the chloroplast (Pyszniak and Gibbs 1992). The association of LHC proteins shows contrasts based on pigmentation when contrasted with LHCs of the higher plants (Gundermann and Büchel 2014).

Fx is present in lot amount in FCPs than the carotenoids present in LHCII; the molar Chl/carotenoid proportion ratio is practically 1:1 and 14:4, separately (Beer et al. 2011; Papagiannakis et al. 2005). Whenever it ties to the protein, Fx goes through outrageous bathochromic shifts, and since it relies unequivocally upon the extremity of the protein climate, a few populaces can be recognized, i.e., Fx red, Fx green, and Fx blue (Premvardhan et al. 2008, 2009, 2013). In diatoms, the Ddx pool is heterogeneous. As of late, three distinct pools of diadinoxanthin cycle shades were proposed. Two of these are bound to extraordinary antenna proteins inside Photosystem I and FCP, individually, and since their turnover is extremely low, they assume no immediate part in the Ddx cycle (Lohr and Wilhelm 2001). The protein-bound diadinoxanthin cycle colors would take an interest in the nonphotochemical extinguishing (NPQ) component, while the lipid-related ones would basically play a cell reinforcement work, searching 1O2 and peroxylipids. Pool of Ddx is all the more firmly associated with a protein-restricting site, which should contrast from the one involved by the Ddx present in low light circumstances (Alexandre et al. 2014). Thylakoid films of diatoms, likewise, contain other xanthophyll like Vx, Ax, and Zx (Lohr and Wilhelm 1999, 2001). In any case, these carotenoids collect just under unambiguous circumstances, e.g., during long haul brightening areas of strength for with. In addition, it has been demonstrated the way that Vx can be either an immediate or a circuitous (through the arrangement of Ddx) forerunner of Dtx.

1.3 Structure and Properties of Pigments of Diatoms

There are two kinds of pigments present in diatoms, i.e., chlorophyll and carotenoids, which are involved in photosynthesis and photoprotection. Chlorophylls trap light energy mostly blue and red wavelength of the electromagnetic spectrum which are used in photosynthesis. Chlorophylls, a light-absorbing green pigment, contain a polycyclic, planar tetrapyrrole structure having central metal ion magnesium in coordination complex. The Chl c pigment is found in diatoms, and the phytyl chain is absent in majority, because of which they are highly conservative structural motifs of the Chl (Zapata et al. 2006). Carotenoids act as accessory light harvesting pigments which capture light energy and feed it to the photochemical reaction center and protect it against photooxidative damage (photoprotection). They are comprised of xanthophylls (which contain oxygen) and carotenes (which are purely hydrocarbons and contain no oxygen).

Chlorophylls absorb maximum light in the violet-blue and red part (Chl a) of the spectrum, but it also displays strong absorption in the yellow-orange (chlorophyll c) parts of the spectrum and thus are optically separated from carotenoids. Photosynthetic pigments are readily identified by their absorption in the visible portion of the electromagnetic spectrum, i.e., from 400 to 700 nm. Chl a absorption peaks at 430 and 662 nm and shows less peaks due to xanthophylls (480 nm) and Chl c (580, 620 nm). The major Chl c absorption peak at 450 nm is weakly visible, being hidden by xanthophylls and Chl a absorption (Fig. 1.1).

1.3.1 Chlorophyll

There are different kinds of pigments present in the photosynthetic organisms, but only two forms of Chls are found in diatoms, i.e., Chl a and Chl c. Chl a is present dominantly and plays a major role in photosynthesis by converting photochemical energy in majority of photosynthesizing organisms, while Chl c (as like Chl b in

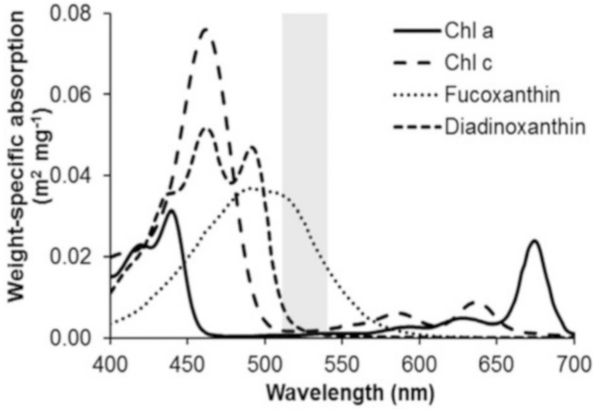


Fig. 1.1 Showing absorption spectra of different pigments found in diatoms (Mulders et al. 2014)

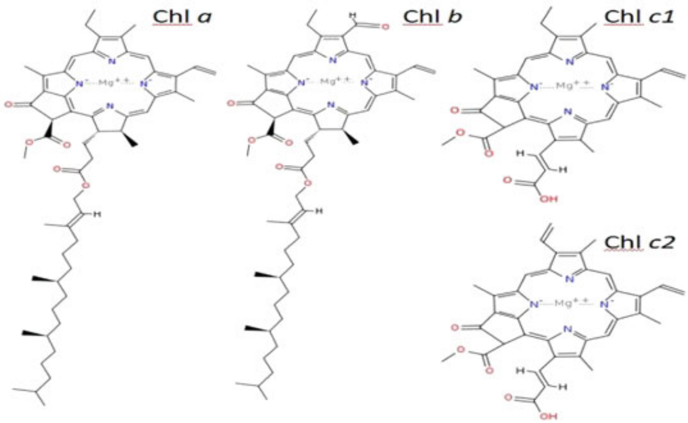


Fig. 1.2 Showing molecular structure of different chlorophyll molecules

plants) mainly acts as an accessory pigments which adequately participates in photosynthesis (Fig. 1.2).

Molecules containing four pyrroles forming a macrocycle (e.g., a porphyrin ring) are classified as closed tetrapyrroles. Chlorophylls (Chls) are conjugated, closed tetrapyrroles to which a cyclopentanone ring has been also added. Tetrapyrroles pigments play essential roles in photosynthesis, in the absorption of sunlight and its conversion into chemical energy, finally used to reduce CO_2. This energy conversion is the foundation for autotrophy in some prokaryotes (e.g., cyanobacteria), eukaryotic algae, and plants. Chlorophyll is found to have natural food coloring, antioxidant, as well as antimutagenic properties. According to estimations, the total natural production of Chls in the biosphere is around 109–1012 tons per year, in which majority of Chls are produced by photosynthetic marine microorganisms (Grimm et al. 2006; Hosikian et al. 2010). Among different sorts of Chls c present in diatoms, the most widely recognized are Chl c1 and c2. The particular construction of a Chl c acquires changes in the retention range to create areas of strength for a (blue) assimilation band in examination with a feeble band in the red district. The proportions of band I (at ~630 nm) to band II (at ~580 nm) are >1 for Chl c1-like chromophores, ~1 for Chl c2-like chromophores, and <1 for Chl c3-like chromophores.

1.3.2 Carotenoids

Carotenoids are a group of nonnitrogenous yellow, orange, or red pigments (biochromes) that are almost universally distributed in living things like plants and diatoms. There are essential types: the hydrocarbon class called carotenes and the oxygenated class called xanthophylls. There are seven forms of carotenoids that had been observed in diatoms where carotenes are represented by β-car and xanthophyll is represented by Fx, Dtx, Ddx, Zx, Ax, and Vx.

All the derivatives of these pigments include isomers and degraded products, which may be found in the cell, but all the trans isomers are present most abundantly and are functionally more active (Fig. 1.3). The possible cause of carotenoid instability could be the occurrence of a conjugated polyene chain in carotenoids, which may be responsible for their oxidation and E/Z isomerization due to heat, light, or chemicals. Membrane physical properties are affected by the structures of carotenoids in cis and transform, which are distinctly allocated in the membrane. The presence of carotenoids changes permeability for tiny molecules and the oxygen, which is related with their protective activity (Subczynski et al. 1991). In contrast to chlorophylls, carotenoids cannot be easily detected by the regular pigment analysis methods because they often get broken down due the destruction of their alternating double bond converting them into colorless compound (Lohr and Wilhelm 2001). Carotenoids generally shows absorption between the range of 400 and 500 nm, and their absorption properties is mainly defined by the conjugation length and the type of the functional groups attached to ionone rings which terminates the polyene chain (Zigmantas et al. 2004). In diatoms, the main light-harvesting carotenoid is Fx, but minor amounts of a 19′-butanoyloxyfucoxanthin-like pigment have also been found in *Thalassiothrix heteromorpha*, a diatom species (Kim et al. 2012). Fx has an allenic link, a conjugated carbonyl, a 5,6-monoepoxide, and acetyl groups, all of which contribute to the molecule's unique structure and spectral features. Its broad absorption band (between 460 and 570 nm) covers much of the gap left by chlorophyll in the green region, unlike other carotenoids. Diatoms also have the β-car, as well as two asymmetrical xanthophylls, Ddx and Dtx, which have an acetylenic group at one of the ionone rings. Vx, Ax, and Zx are three more xanthophylls that may be present (Lohr and Wilhelm 2001). It has also been found that these carotenoids assemble only at times like long-time exposure with strong light.

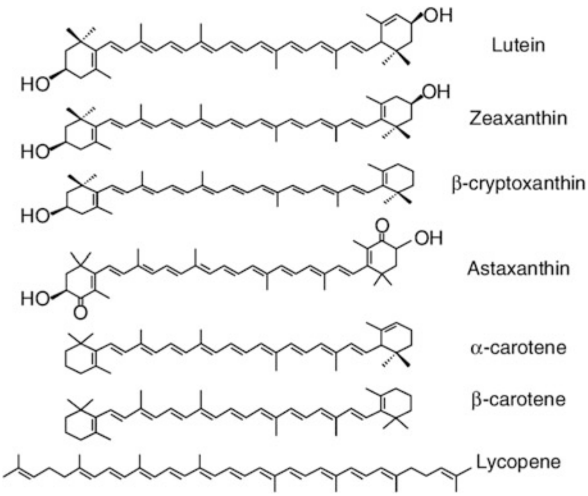


Fig. 1.3 Structures of various pigment derivatives

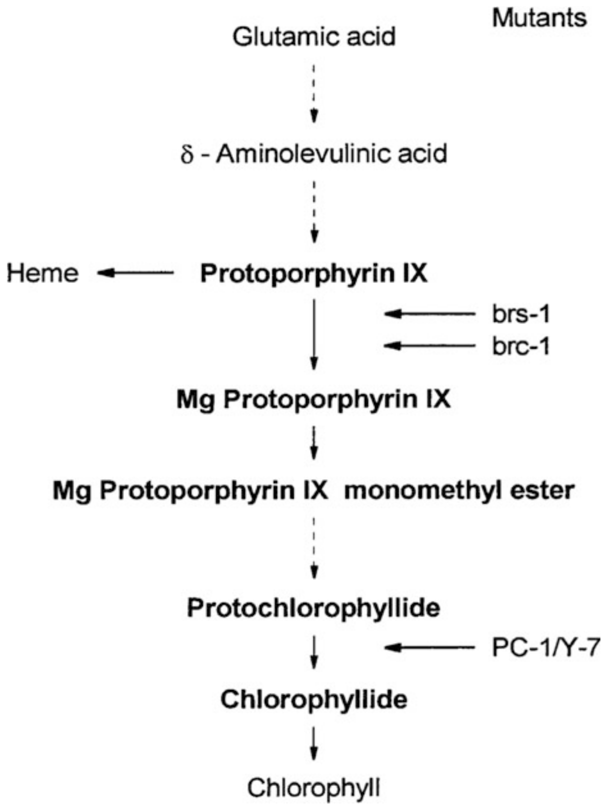
1.4 Biosynthetic Pathways of Pigments

1.4.1 Chlorophyll: Biosynthesis

The chlorophyll synthesis pathway has been extensively explored in higher plants and some algae groups, although it has been poorly investigated in diatoms (Kuczynska et al. 2015). However, all photosynthetic organisms share the same basic characteristics (Fig. 1.4). Chl production requires three universal steps: the creation of aminolevulinic acid, its transformation into Mg-porphyrins, and protochlorophyllide conversion to Chl (Grimm et al. 2006).

The first step depends on the cyclization of tetrapyrrole, the introduction of Mg leading to the formation of diviny-PChlide, and its reduction into PChlide a. Next, photo-independent PChlide oxidoreductase (DPOR) and photodependent enzyme (LPOR) catalyze the hydrogenation of PChlide to Chlide, which promotes the formation of Chl a in a further step. Several isoforms of LPOR have been found in some diatom species (Hunsperger et al. 2015). The final step is the insertion of phytol residues associated with the MEP pathway, which is also used for carotenoid formation. The molecular structure of Chl c may indicate that PChlide is a precursor of biosynthetic pathways where oxidation and dehydration are essential, but the enzyme that performs these steps has not been reported (Porra 1997). In general, the facts about Chl biosynthesis and the enzymes that catalyze each step are not clearly understood yet.

Fig. 1.4 Biosynthetic pathway of chlorophyll pigment



1.4.2 Carotenoid: Biosynthesis

Carotenoid biosynthesis occurs by two pathways which are methylerythritol phosphate (MEP) and mevalonate (MEV). Their occurrence is not well understood, but a few studies show that it depends on the growth rate (Cazzonelli and Pogson 2010). The products of both the pathways are dimethylallyl diphosphate (DMAPP) and its isomer, isopentenyl pyrophosphate (IPP) (Stauber and Jeffrey 1988). The next steps on the pathway to lycopene synthesis are the conversion of DMAPP to geranylgeranyl pyrophosphate (GGPP), which is catalyzed by GGPP synthase; then to phytoene by phytoene synthase (PSY); afterwards to ζcarotene, which is catalyzed by phytoene desaturase (PDS); and, finally, the product of ζcarotene desaturase (ZDS), which is lycopene (Bertrand 2010). Lycopene as a long and straight atom is cyclized by lycopene βcyclase (LCYB) to βvehicle, having two βionone rings at the two closures of the yield. In the following stage, xanthophyll is first shaped, and this response requires hydroxylation. Nonetheless, a quality encoding βcarotene hydroxylase (BCH) was not found in the diatom genome, and another that resembles LUT1 has been proposed as a hypothetical catalyst to make the development of Zx from βvehicle conceivable (Coesel et al. 2008). Two further light-reliant and reversible responses lead to Vx development by means of the moderate item Ax. Both are catalyzed by Vx deepoxidases (VDEs) in high light circumstances; however, switch responses are catalyzed by Zx epoxidases (ZEPs) in low light or in obscurity. Vx, on the other hand, is formed from Zx by β-cryptoxanthin (Cx) and β-cryptoxanthin epoxide (CxE) (Lohr and Wilhelm 1999). Further progress leading to the assembly of Fx, Ddx, and Dtx remains ambiguous due to the lack of information on the chemicals involved at the same time. Nevertheless, two models of potential conversions from Vx to Fx have been introduced so far. The main model proposed Vx as a precursor of Ddx, Dtx, and Fx (Lohr and Wilhelm 2001) with a response of Vx propagating to Fx through Dtx and Ddx. This theory was affirmed tentatively utilizing norflurazon, which hinders carotenoids, and was utilized after the aggregation of Vx. A rise in Fx level can be seen in low light. Another model depending on hypothesis about compound properties of these neoxanthin (Nx) and xanthophylls was viewed as an antecedent of Fx and Ddx (Dambek et al. 2012). The arrangement of Fx requires two adjustment steps: the ketolation of Nx and acetylation of a fucoxanthinol may occur, and, to help one of these theories, the distinguishing proof of the chemicals is vital. The most impressive methodology for this is to search for qualities which encode the proteins of interest on information basis. Notwithstanding, LCYB imparts amino corrosive character to NXS up to 64% which takes part in Nx creation, albeit no LCYB-like NXS in earthy-colored ocean growth was distinguished (Mikami and Hosokawa 2013). It is essential to uncover the entire xanthophyll biosynthetic pathway due to the numerous valuable chances to additional examinations and furthermore to plan transgenic creatures with an expanded xanthophyll level (Fig. 1.5).

1.5 Commercial Use of Photosynthetic Pigments

1.5.1 Fucoxanthin

Fucoxanthin ($C_{42}H_{58}O_6$) is a commercially important carotenoid. Diatoms, along with brown seaweeds, have been extensively utilized for in vitro and in vivo production of FX using different strains by modifying various metabolic and environmental factors (Bauer et al. 2019). FX has attracted significant interest in the past few decades because of its versatile functionality that includes antioxidant, anticancer, anti-inflammatory, and anti-obesity effects (Gammone and D'Orazio 2015). Due to its greater potential for preventing disease (better than β-carotene and astaxanthin), its uses in the nutraceutical and cosmetic industry and, consequently, the demand for FX are increasing (Lourenço-Lopes et al. 2021). The market and prices are burgeoning for FX produced from diatoms. Studies demonstrate that diatoms produce at about ten times more FX per gram of DW than any brown alga. The main goal is to increase the number of such useful products along with the economy of the process. However, the main challenges are to select/identify a strain of diatom that can produce consistent biomass and biomolecules under varying

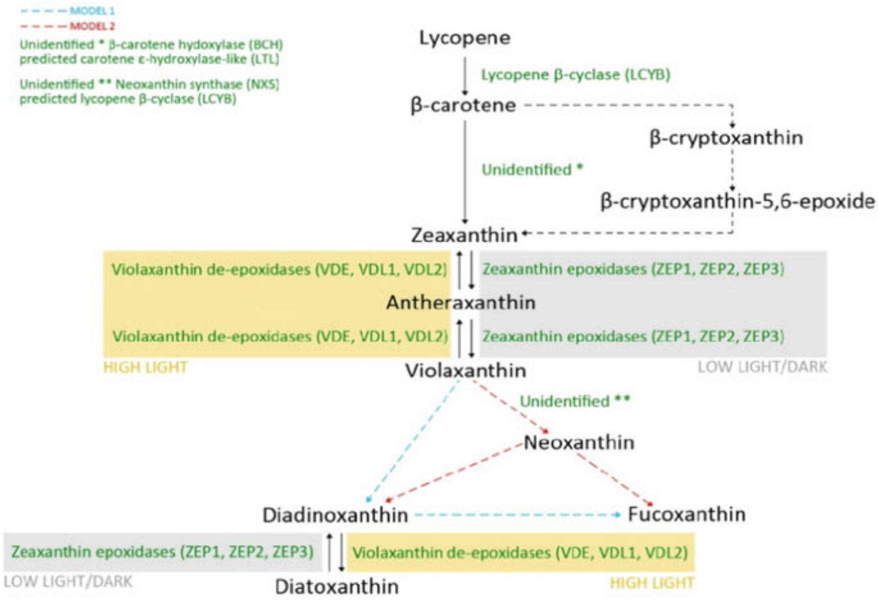


Fig. 1.5 Image showing biosynthetic pathway of photosynthetic carotenoids in the diatom from lycopene to fucoxanthin and diatoxanthin (Kuczynska et al. 2015)

conditions in outdoor cultivation. The methods to culture diatom at a commercial scale exist; however, there are certain limitations like identification and isolation of the best diatom strains for FX production, standardization of protocols to obtain pure cultures, and optimal nutrient requirements in a photobioreactor-based production system. Further, more studies are required focusing on reducing the input cost during downstream processing to obtain high quality and quantity of FX at reasonable price and purity. In addition, to efficient culture methods, critical information of the pathways involved in producing bioactive algal metabolites is required, including the identification of genes that could be used for genetic engineering. The current focus of algal engineering is on obtaining transformants with higher lipid accumulation to change the fatty acid composition. Optimization of cultivation conditions, microalgal engineering, and epigenomic reprogramming of algal strain can increase FX production. Not only FX but also intermediates have potential commercial application (Fig. 1.6).

1.5.2 *Diatoxanthin and Diadinoxanthin*

Diatoxanthin are a type of carotenoids which dissipate energy by means of nonphotochemical quenching (Lavaud et al. 2004). These carotenoids have great application in the food, cosmetic, and pharmaceutical industries; they also possess

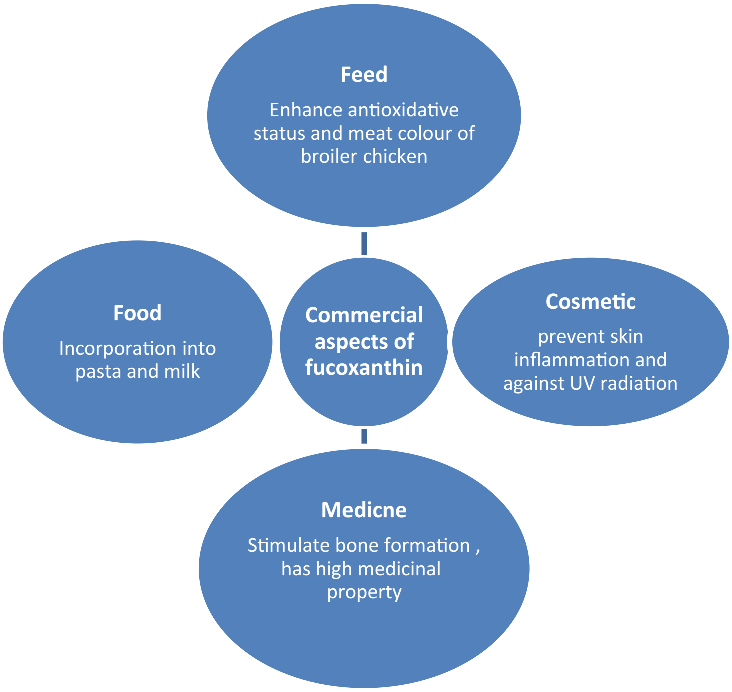


Fig. 1.6 Image showing commercial applications of fucoxanthin pigment

neuroprotective effects (Pangestuti and Kim 2011). Diatoms display diadinoxanthin cycle in which interconversion between epoxidized diadinoxanthin and epoxy-free diatoxanthin occurs. Two diatom-specific carotenoids are found in the diadinoxanthin cycle, an important mechanism which protects these organisms against photoinhibition caused by absorption of excessive light energy. This unicellular alga is a cosmopolitan marine pennate diatom. Since both diadinoxanthin and diatoxanthin occur only in few algal groups like diatoms, these pigments might be considered as diatom-specific carotenoids.

1.5.3 Zeaxanthin

Zeaxanthin is a carotenoid molecule that has antioxidant potential with several health benefits such as reducing the risk of age-related macular degeneration, glaucoma, and cataracts. *Phaeodactylum tricornutum*, a diatom, synthesizes zeaxanthin by zeaxanthin epoxidase and zeaxanthin de-epoxidase which have been proposed from the available genome sequence. These two enzymes may be involved in the two different xanthophyll cycles which operate in *Phaeodactylum tricornutum*.

1.5.4 Lutein

Lutein is a natural antioxidant and has drawn interest for its health-promoting functions. Lutein has potentials in free radical scavenging for skin health and can also prevent age-related macular degeneration (AMD) and Alzheimer's disease (AD) (Roberts et al. 2009). Absorbed lutein can accumulate in human retina, filter blue light, and, thus, protect eyesight. Orange-yellow fruits like mango and green leafy vegetables like broccoli are dietary sources of lutein .The marigold flower is the main source of natural lutein and lutein esters (Breithaupt and Schlatter 2005). However, there are some drawbacks of this source, such as mandatory harvesting in specific seasons and time-consuming petal separation. Other sources containing lutein also have such disadvantages as low concentration (corn residues, leafy green vegetables) and low bioavailability (egg yolk, crustaceans). The production of lutein from microalgae may avoid these troubles. Microalgae like diatoms can accumulate considerable biomass concentrations and accumulate lutein under suitable culture conditions. Even as compared with marigold-originated lutein, lutein in microalgae exists in free form. If in the coming future we became able to develop techniques to extract lutein from diatoms, it will prove to be beneficial to us by commercial aspect and medical level.

1.5.5 β-Cryptoxanthin

β-Cryptoxanthin has provitamin A activity. This carotenoid can supply one vitamin A molecule based on structure. This is likely due to the bipolar nature of *β*-cryptoxanthin. *β*-cryptoxanthin is associated with lower rates of lung cancer and improved lung function in humans. In tissue culture, *β*-cryptoxanthin has a direct stimulatory effect on bone formation and an inhibitory effect on bone resorption. However, the process of β-cryptoxanthin esterification in diatom is rarely investigated, and their roles in plants and animals are not well determined yet. In addition, the role of β-cryptoxanthin that involved therapeutic and immune-enhancing properties in human should be investigated further. Though β-cryptoxanthin is synthesized in our body, due to its medicinal values, we have to increase its consumption during diseases and for that we have to increase its productivity. Although they are present in plants with high amount, to fulfill our requirements, we have to find the measure to enhance its productivity for commercial purpose, and the best way is extraction of beta cryptoxanthin from diatoms. These carotenoids can also be found in diatoms, so there is a need to devise some cost-effective and time-saving methods to extract them from diatoms.

1.5.6 Chlorophyll: Commercial Aspects

Earlier chlorophyll were chiefly extracted from green leaves; however, emerging tools, techniques, and methods have been developed that rely on diatoms, cyanobacteria, or microalgae (Tong et al. 2012; Kong et al. 2014; Wrolstad and Culver 2012; Humphrey 2004; Heydarizadeh et al. 2013). It was discovered that the amount of chlorophyll taken from a given algae species was greatly dependent on its growth stage. Microalgae collected during the stationary growth phase were shown to have substantially more chlorophyll a than those extracted during the logarithmic phase (Schumann et al. 2005) (Fig. 1.7).

1.5.7 As Food Colorants

To increase the marketability of the products, special care is taken during food processing to retain and/or restore the green color of Chls and to avoid the formation of their less attractive colored and/or less healthy breakdown products in all

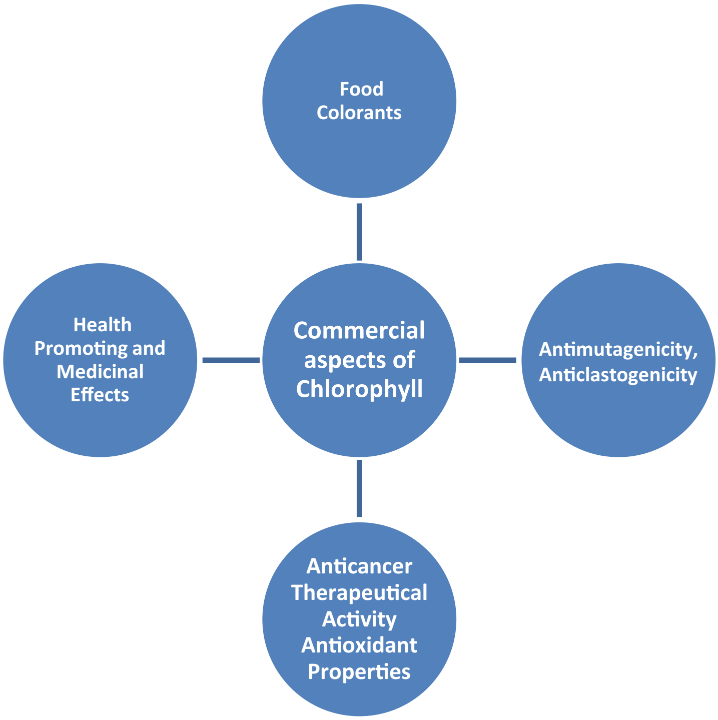


Fig. 1.7 Image showing commercial applications of chlorophyll pigment

commodities containing Chls (either inherently or as color additives or as medicinal products). One key issue that restricts usage of Chls as direct food colorants is that the central Mg is easily lost during processing (Arnold et al. 2012). This can be solved by replacing this ion with other metals within the macrocycle resulting in more stable Chl-metal complexes. The other limiting factor is the high hydrophobicity of the pigment molecule imparted by its long hydrophobic phytol chain (derived from phytol—C20H39OH) and by a fifth ring (cyclopentanone) in the macrocycle (Tumolo and Lanfer-Marquez 2012). Chemical modification of these groups can increase the water solubility of Chl derivatives and provides water-soluble food colorants.

1.5.8 For Health Promoting and Medicinal Effects

Effects of chlorophylls and their derivatives first of all in humans. The role of dietary Chl metabolites and derivatives in animals and humans is reviewed in detail elsewhere (Ma and Dolphin 1999; Ferruzzi and Blakeslee 2007; Ulbricht et al. 2014; Nagini et al. 2015). Ideally, medicinal studies with Chl derivatives should use a single compound with verified purity and/or with stable and well-characterized composition (Dashwood 1997; Chernomorsky 1994). However, often this is not the case. Most studies on, for instance, cancer-related research of Chl derivatives used the relatively cheap, stable, commercially available, and water-soluble food-grade Cu-chlorophyllin, the composition and purity of which was often not standardized (Dashwood 1997; Chernomorsky 1994).

1.5.9 For Antioxidant Properties

Most neurodegenerative and inflammatory diseases, cancer, diabetes mellitus, atherosclerosis, reperfusion injury, aging processes, etc., can be associated with excessive formation of free radicals resulting in oxidative stress and/or impaired antioxidant defense system of the organism. However, disease may be prevented, or the symptoms or effects may be alleviated by the therapeutic use of different antioxidants. It is well-established that Chls and their derivatives (especially Na-Cu-chlorophyllin) (Ferruzzi et al. 2002a, b; Lanfer-Marquez et al. 2005; Kumar et al. 2001, 2004) have antioxidant properties (Ferruzzi and Blakeslee 2007). They act as effective scavengers for reactive oxygen species (ROS), e.g., singlet oxygen (Nakamura et al. 1996; Kamat et al. 2000), hydroxyl radical (Boloor et al. 2000), and hydrogen peroxide (Kumar et al. 2001), and they also inhibit lipid peroxidation both in vitro and in vivo in splenic mice lymphocytes (Kumar et al. 2004) and ex vivo in mice brain, liver, and testis (Kamat et al. 2000). Several natural Chl derivatives were shown to inhibit hydroperoxide formation by lipid peroxidation during the exposure of linolenic acid to ferric nitrilotriacetate in the dark: Chl a had the strongest antioxidant activity.

1.5.10 For Photodynamic Therapy (PDT)

Several Chl precursors, analogs, derivatives, and metabolites (e.g., 10-hydroxypheophytin a) are being used as photosensitizers in medicine for PDT of cancer. During PDT, direct and selective tumor cell destruction is obtained by selective accumulation and light-activated ROS-mediated photo toxicity of photosensitizing agents within tumor cells and/or the surrounding vasculature. During this process, excited photosensitizers transfer their excitation energy to surrounding molecules (e.g., to oxygen) to produce singlet oxygen and other ROS and free radicals. In addition to substantial phototoxicity, photosensitizers used in PDT should preferably have low or no dark toxicity and low uptake by normal (non-cancer) cells. One of the major advantages of Chl derivatives in PDT—for instance, when compared with Photofrin, a hematoporphyrin is widely applied in PDT—is that they absorb better penetrating light (wavelengths above 650 nm) and can be, thus, used to treat larger and more deeply seated tumors (Rapozzi et al. 2009). In addition, they may be used to detect tumor cells by fluorescence (You et al. 2011).

1.6 Chemoprevention, Antimutagenicity, Anticlastogenicity, Antigenotoxicity, and Anticancer Therapeutic Activity

Several in vitro and in vivo data indicate that natural Chls (both Chl a and Chl b) and their most important dietary derivatives like chlorins, pheophytins, etc. (Chernomorsky et al. 1999; Ferruzzi et al. 2002a, b) but also Na-Cu-chlorophyllins (used in most studies) can have antimutagenic, mutagen trapping, antigenotoxic, anticlastogenic, and anticarcinogenic effects and can modulate xenobiotic metabolism both in simple model organisms (e.g., Salmonella), in animals (e.g., *Drosophila*, mice, and rats), and in humans (Nagini et al. 2015; Chernomorsky et al. 1997, 1999; Park and Surh 1998; Breinholt et al. 1999; Jubert et al. 2009). Chlorophyll and its derivative, Na-Cu-chlorophyllin, is found to prevent liver cancer in adults exposed to the carcinogen aflatoxin (Egner et al. 2003; Jubert et al. 2009); hence, Chl derivatives (especially chlorophyllin) are available as dietary supplements with anticarcinogenic/chemopreventive effect.

However, some authors have found that the tumor-preventive effects of chlorophyll and their derivatives can be explained by their absorption and their observed postabsorptive chemo-preventive effects on enzymes and other processes (Tumolo and Lanfer-Marquez 2012; Egner et al. 2000; Castro et al. 2009).

1.7 Conclusion

This review summarizes the biosynthetic pathways and focusses on commercial aspects of the photosynthetic pigments in diatoms. It also exposes that chlorophyll and carotenoids, the major photosynthetic pigments present in diatoms, have a great range of applications. However, unmodified chlorophylls are too labile for most practical use, but some derivatives are used due to their coloring effect, tissue growth stimulating effect, antioxidant, and antimutagenic properties, and this chlorophyll can be potentially extracted from diatoms. Even though not all diatom chemicals are known, there is ongoing study to uncover, identify, and examine their properties due to the relevance of these creatures. In a species of marine diatoms *Haslea ostrearia*, a blue-colored water-soluble pigment has been isolated which has antioxidant, anti-microbial, growth-inhibiting, and allelopathic properties (Gastineau et al. 2014). This pigment itself shows the potential of diatoms and their less-explored pigments. Chlorophyll is a most valuable bioactive compound that can be extracted from diatom biomass. It has various uses for its antioxidant and antimutagenic properties; besides, it is commonly used as natural food coloring agent. Nowadays, chlorophyll is being frequently used in the medicine field as remedy and diagnostics. Chlorophyll molecules are used in cancer therapy as a pharmaceutical application. Their roles as modifier of genotoxic effects are becoming increasingly important, besides it being known to have multiple commercial uses.

Last but not least, it is worth mentioning that although diatoms are being extensively used for commercial purposes, the pigments of diatoms have received less attention. Various pigments are yet to be isolated from diatoms which can have possible commercial applications. This is since our knowledge about the photosynthetic pigment and their derivatives present in diatoms is still limited.

Conflict of Interest The authors confirm that this article content has no conflict of interest.

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