PIGMENTATION FROM MICROALGAE

Abstract

The food, nutraceuticals, and cosmetics industries all use microalgal pigments extensively. .Pharmaceutical aquaculture, as well as the cosmetics industry. Some microalgae have been gathered. For decades, people have relied on it for food and health care. Microalgae is now used in the nutraceutical business. They have evolved as novel bioresources for the production of food and aquafeed. Bioenergy, food and feed, and wastewater bioremediation are all encouraged. Both light sources Photoautotrophic microalgal production occurs in both natural and artificial contexts. Carotenoids are antioxidants. Tetraterpene pigments having yellow, orange, red, and purple colours. Carotenoids are antioxidants. These shades are widely distributed in the natural world, including photosynthetic microbes, certain organisms and algae, fungal vegetation, and even tissue from humans. These materials are in high demand across a number of industries, including pharmacy, medical treatment, beauty products, the chemical industry, aquaculture, energy generation, and agriculture for both animal feed and wholesome meals. Microalgae have gotten less attention than seaweeds, yet they offer advantages such as rapid growth, high photosynthetic efficiency, and the potential to be cultivated in industrial settings.

Keywords: Microalgal pigments, Bioenergy, photosynthetic bacteria, photosynthetic.

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I. INTRODUCTION

Microalgal pigments have extensive applications in various industries such as food, nutraceutical, pharmaceutical, aquaculture, and cosmetics (**see Figure 1**). They have also proven invaluable in clinical and scientific settings, where they serve as effective labels for antibodies and receptors (1). Additionally, phycobiliproteins exhibit hepatoprotective, neuroprotective, anti-inflammatory, and antioxidant properties (2). Microalgae are increasingly utilized in aquaculture for diverse purposes, including providing live feed for the larviculture sector, serving as premixes for feed formulation and supplementation, contributing to bioremediation for improved water quality (3), fostering the development of highly beneficial organisms, and enhancing animal coloration through astaxanthin supplementation. Notably, specific microalgae have been employed as food and medicine for thousands of years. There is a rising preference for wholesome, unadulterated, and clearly labelled food goods as customers focus more on their health and food safety (4). lipids, carbohydrates, vitamins, minerals, colours, and polyunsaturated fatty acids (PUFAs), all of which have vital commercial and health relevance, are among the value-added products that microalgae provide as a significant reservoir for (5). Notably, "microalgae" include prokaryotic cyanobacteria and eukaryotic photosynthetic microorganisms, both of which use photosynthesis to change light energy into chemical energy. In microalgae, there are three main categories of pigments: carotenoids (usually comprising around 0.1-0.2% of the dried weight, DW, but can be as high as 14% in certain organisms), chlorophylls (constituting 0.5-1.0% of DW), and phycobiliproteins (PBPs), which make up approximately 8% of DW. These pigments play a crucial role in facilitating photosynthesis and cell development. Compared to other natural pigment sources (such asbroad range of health uses. Microalgal pigments have an advantage over other food colorings since they may produce a wide variety of appealing tints, colors, and natural tones in meals. that can imitate the colour of real food (6). Furthermore, their greatest advantage stems from the microalgae's cultural properties. Current research is exploring various cultivation techniques to enhance pigment accumulation in different microalgae species. Some notable examples of active pigments that have been successfully scaled up for industrial production include PBPs, a blue pigment obtained from spirulina, astaxanthin, a yellow-to-red pigment derived from Haematococcus, and β-carotene, a yellow pigment sourced from Dunaliella. These pigments are widely utilized across various industries, including food, nutraceuticals, pharmaceuticals, aquaculture, cosmetics, and more.
During the process of pigment synthesis in microalgae, several biotic and abiotic factors may influence the quality of the final product (7).Microalgae synthesize pigments during vegetative development or under stress. The efficiency of generating pigment is markedly increased by the introduction of new trophic modes and strategies (8). Additionally, the extraction, purification, and food processing processes can modify or destroy pigments' structural integrity, which compromises their ability to provide food with color and nutrition. The molecules responsible for capturing light and sending it to reaction centers, both of which are necessary for photosynthesis, are known as microalgal pigments. In thylakoid membranes, they are arranged into complexes called antennae. While it is situated next to and parallel to the cell surface of cyanobacteria (prokaryotic microalgae), this membrane is present inside the chloroplasts of eukaryotic microalgae (9,10,11). Due to their ability to create and store precious pigments, microalgae are very desirable for industrial production. Furthermore, they have definite advantages over other plant-based sources. These benefits include their extraordinary geographic diversity and vast distribution, as well as their lack of need on cultivable land.

Additionally, the fact that they are photosynthetic may result in decreased manufacturing costs. Since microalgae don't need additional carbon sources like heterotrophic organisms do and some species can fix nitrogen on their own, no additional nitrogen is needed (12). These microorganisms are already harnessed by various industries to produce pigments and a range of other valuable products. Pigments serve as a primary source of revenue for many enterprises, especially in sectors like food, cosmetics, and healthcare, even though pigment market prices surpass those of other microalgal components (13). Among the most commonly utilized microalgae for pigment production are Dunaliella salina, Arthrospira platensis, and Haematococcus pluvialis, which are employed to generate beta-carotene, astaxanthin, and C-phycocyanin, respectively. Additionally, ongoing efforts are being directed towards the pilot-scale production of lutein using Muriellopsis sp. and Scenedesmus almeriensis (14).

Microalgae and Pigments: Microalgae constitute a diverse group of cryptogamic plants encompassing 13 major phyla along with numerous lesser-known minor ones. They exhibit a wide range of structural forms, which can be siphonaceous, filamentous, colonial, or unicellular in nature. One of the prominent phyla within microalgae includes cyanobacteria, which are oxygenic photosynthetic prokaryotes distinguished by their diverse morphology, physiology, ecological roles, biochemistry, and various other characteristics. In contrast, cryptophytes are unicellular and are found in both freshwater and marine environments, while chlororophyta are algae that can take on filamentous, siphonous, multicellular, unicellular, and thallus forms, primarily inhabiting freshwater environments. The majority of dinophytes are unicellular organisms featuring two distinct flagella (15). Please refer to Table 1 for a detailed list of pigments present in each of these microalgae phyla.

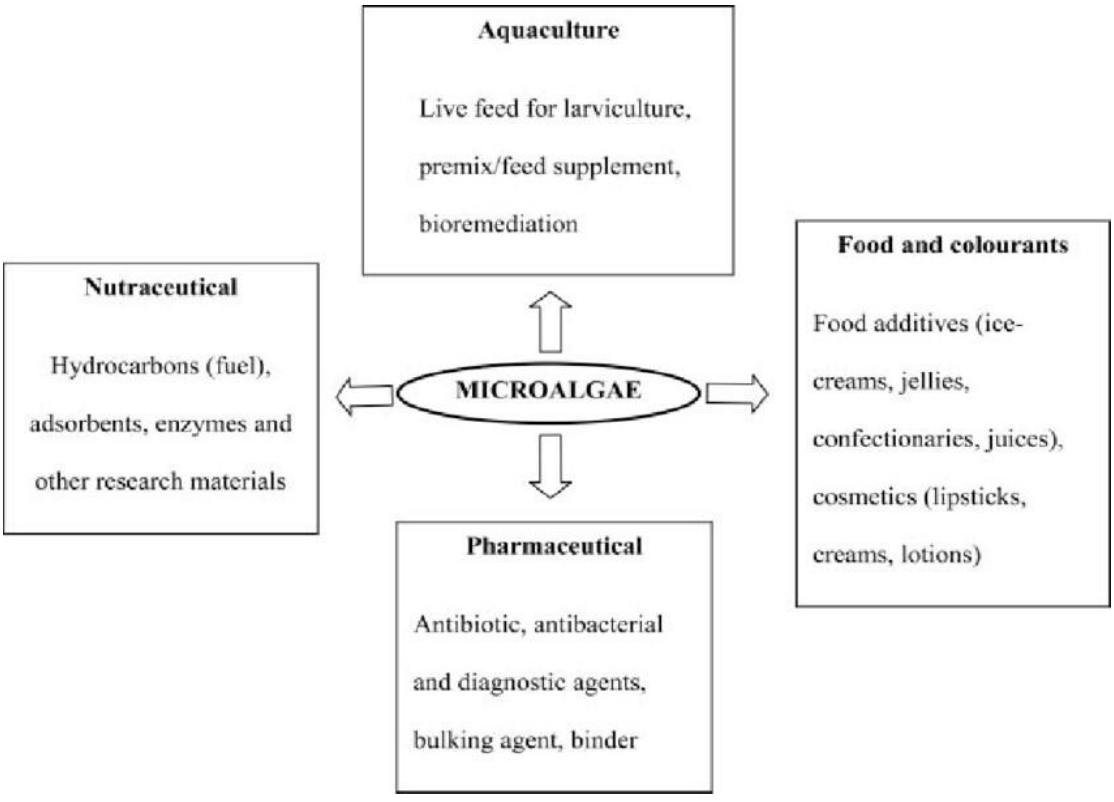

Figure 1

Table 1: Various Microalgal Pigments

Phylum	No. of genera/species	Common name	Pigments	Pigments
Chlorophyta	Approximately 500/16,000	Green microalgae	Chlorophyll a, b, b-carotene, prasinoxanthin, siphonaxanthin, astaxanthin	16,17
Diatomophyceae / Diatoms	>200/100,000	Brown microalgae	Chlorophyll a and c, b-carotene, fucoxanthin, diadinoxanthin	16,17
Cryptophytes	About 12–23/200	Cryptomonads	Chlorophyll a and c, carotenoids and Phycobiliproteins	16,17
Cyanobacteria	Total 10/>2000	Blue-green microalgae	Chlorophyll a, xanthophyll and Phycobiliproteins	16,17
Euglenophyta	About 40/900	Euglenoids	Chlorophyll a and b, diadinoxanthin, neoxanthin, and b-carotene	16,17
Dinophyta	About 130/220	Dinoflagellates	Chlorophyll a, c, carotenoid (b-carotene), peridinin	16,17

II. CHARACTERISTICS OF MICROALGAL PIGMENTS

Microalgae contain three primary categories of photosynthetic pigments: phycobilins, carotenes, and carotenoids. Notably, phycobilins are water-soluble, contrasting with the fat-solubility of carotenoids and chlorophylls. Chlorophylls, which are fundamental to photosynthesis, come in three recognized forms: chlorophyll-a, chlorophyll-b, and chlorophyll-c. The chlorophyll molecule possesses a tetrapyrrole-ringed porphyrin macrocycle structure (18). Within this structure, one of the pyrrole rings is connected to a single isocyclic ring, forming the phorbin structure (19). Due to these structural distinctions, chlorophyll-a and chlorophyll-b exhibit varying pigment colors and have distinct maximum absorbance ranges, measuring 642–652 nm and 660–665 nm, respectively (18). Furthermore, the presence of weak acids, oxygen, or exposure to light can induce the degradation of chlorophyll molecules, leading to the formation of various metabolites.

Carotenoids consist of a 40-carbon polyene chain and possess diverse molecular structures that give rise to specific chemical properties, including light-absorption capabilities essential for photosynthesis. Carotenoids can incorporate cyclic and oxygen-containing functional groups into their structure. Consequently, oxygenated derivatives of hydrocarbon carotenoids are commonly referred to as xanthophylls. Oxygen in hydrocarbon carotenoids is found as hydroxyl groups (e.g., lutein), keto-groups (e.g., cantaxanthin), or a combination of both (e.g., astaxanthin) (20). Phycobiliproteins display a range of spectral characteristics due to the unique absorption spectra of their constituent bilins (23). In cyanobacteria and red microalgae, four major families of phycobiliproteins are recognized: allophycocyanin (APC, bluish-green), phycocyanin (PC, blue), phycoerythrin (PE, red), and phycoerythrocyanin (PEC, orange). Each class has a specific absorbance maximum, with allophycocyanin at λAmax 650-655 nm, phycocyanins at λAmax 615-640 nm, phycoerythrin at λAmax 565-575 nm, and phycoerythrocyanin at 577 nm. Their emission of light occurs at 660 nm, 637 nm, 577 nm, and 607 nm, respectively.

According to Arad and Yaron (1992), a microalgal extract from Pseudomonas aeruginosa displays red fluorescence with a maximum emission at 642 nm and a blue color with a maximum absorbance at 620 nm. C-phycocyanin serves as the primary phycobiliprotein in most cyanobacteria. This protein comprises two polypeptide chains, each containing methionine, as identified in wild-type Oscillatoria agardhii microalgae cells (24, 25). These chains are connected by a disulfide bridge and contain at least one chromophore group each. The newly discovered chains exhibit a similar structure in terms of amino acid composition, peptide mapping, and amino-terminal sequence.

III. FACTORS AFFECTING THE MICROALGAL PIGMENT PRODUCTION

Presently, one of the most efficient approaches for producing natural pigments is through microalgae fermentation. Pigments derived from industrially cultivated microalgae offer several advantages when compared to those obtained from plants and aquatic animals. These advantages encompass controlled manufacturing processes, straightforward extraction methods, high production yields, a constant supply of raw materials, and the absence of seasonal variations. Every small change in environmental circumstances during the culture stage has the potential to affect pigment synthesis and molecular structure, which can modify the end products' market acceptability and bioaccessibility.

1. **Light:** Light is the primary driving force responsible for converting inorganic carbon into organic molecules in phototrophic organisms. Microalgal growth can be significantly enhanced through light utilization, but this enhancement is subject to specific conditions of light intensity and photoperiod regulation (26). Among the factors governing cell photosynthesis and pigment production, light intensity stands out as the most conspicuous and controllable element. When light exceeds its tolerance threshold, it can have detrimental effects on photosynthesis, ultimately leading to damage to the photosynthetic machinery. The production of chlorophyll and phycobiliproteins represents adaptive responses to light availability. Cyanobacteria with lower specific maintenance energy ratios tend to exhibit a faster rate of phycobiliprotein production. In certain situations, the impact of light quality on photosynthetic pigments goes beyond merely light intensity and can influence factors such as cell maturity, culture density, light penetration depth, and the nutritional composition of the growth medium. Discontinuous lighting methods, such as

light/dark photoperiod cycles and the flashing light effect, have been employed to enhance light availability. In industrial culture settings, the flashing light effect, for instance, can increase the rate of astaxanthin synthesis in H. pluvialis per photon by a factor of four when compared to continuous light sources. Moreover, adjusting the photoperiod effectively regulates the levels of chlorophyll in microalgae (27, 28).

2. **Temperatures:** Elevated temperatures often play a facilitating role in the synthesis of microalgal pigments. Research has established that a temperature range of 25–28 degrees Celsius is optimal for promoting the growth of chlorophyll. Temperatures higher than this range may induce osmotic pressure that can harm cellular structures (29). In specific cases, the highest production of astaxanthin is observed at 28 degrees Celsius for H. pluvialis and at 30 degrees Celsius for C. zofingiensis (30, 31). Blue-green microalgae can produce carotenoids like β-carotene most effectively under high-temperature conditions (32). For instance, H. pluvialis and Phormidium autumnale have demonstrated the highest carotenoid yields when total carotenoid synthesis was carried out at these temperatures (33, 34). Growing D. salina at 30 degrees Celsius maximizes β-carotene production (35).

   When it comes to lutein production, the microalgae Muriellopsis sp., C. protothecoides, C. zofingiensis, and Neospongiococcus gelatinosum achieve their highest yields when cultured at 28 degrees Celsius (36). As for phycobiliprotein (PBP) generation, the optimum temperatures vary for different species. S. platensis, Anabaena sp., Nostoc sp., and Synechococcus sp. demonstrate peak PBP production at 25, 30, 35, and 36 degrees Celsius, respectively (37).

3. **Culture Media:**

   - **Nitrogen:** Nitrogen plays a pivotal role in microalgae, primarily driving the synthesis of proteins, chlorophyll molecules, nucleic acids, and supporting their overall growth and proliferation. The absence of adequate nitrogen in microalgae has been associated with a range of cellular responses, including an increase in the generation of free radicals. Nitrogen deficiency can lead to a significant elevation in the concentration of carotenoids, as they are recognized as a defense mechanism against photo-oxidative stress resulting from a compromised photosynthetic electron transport chain. In nitrogen-depleted conditions, numerous blue-green microalgae, such as Anabaena sp., have been observed to produce substantial amounts of phycobiliproteins (PBPs), while Fischerella sp. displays the opposite tendency (38).

   - **PH and Salinity:** pH levels can have a significant impact on nutrient availability and solubility within a culture environment, but little is currently understood regarding its effect on pigment production in microalgae. It has been established that pH values within the range of 5.0 to 8.5 are conducive to microalgal growth (26). pH regulation is crucial for controlling substance solubility and nutrient uptake in cells. In the case of S. platensis, it was found that chlorophyll a (10.6 mg/g DW), carotenoids (2.4 mg/g DW), and C-PC (91 mg/g DW) reached their peak production levels at pH 8.5, while PC (159 mg/g) was produced most abundantly at pH 9.0 (39). However, alterations in pH under certain microalgal culture conditions can impede the formation of carotenoids and chlorophyll.

Osmotic conditions significantly influence pigment accumulation, with salinity playing a pivotal role in the commercial production of pigments by both marine and freshwater microalgae. Most microalgae exhibit maximum production levels at lower salinities, typically around 2–3 parts per thousand (ppt), leading to reduced content of chlorophylls and total carotenoids (40). Nevertheless, blue-green microalgae tend to produce more β-carotene as salt concentrations increase. Consequently, at a salinity range of 10-15 ppt, the blue-green microalgae Anabaena sp. (135.73 mg/g) and Oscillatoria sp. (66.7 mg/g) achieved their highest production levels of phycobiliproteins (PBPs) (41).

- **Micronutrients:** Even though they are needed in small quantities, micronutrients like manganese, iron, and zinc play essential roles in pigment metabolic processes. A reduction in iron levels can lead to a decrease in chlorophyll content in C. pyrenoidosa because iron is vital for the tricarboxylic acid cycle and other metabolic pathways. The concentration of astaxanthin is influenced by both the electrical valency of iron and counter ions (32). The presence of iron in the growth medium can enhance astaxanthin production, with an effective increase achieved by including 18 mM Fe2+-EDTA. Furthermore, the level of β-carotene significantly increases with the introduction of 450 mM FeSO4 (42). Copper is required as a cofactor for metalloenzymes in numerous metabolic processes, but excessive amounts can have detrimental effects on microalgae growth. Elevated levels of zinc and copper have been associated with peroxidation of chloroplast membranes, induced by the generation of free radicals, resulting in a reduction in chlorophyll content. Magnesium, a primary chlorophyll ion, serves as a cofactor for essential enzymes in pigment formation and the pigment metabolic pathway (43). Chlorophyll levels in Chlorella sp. cells ultimately decrease with or without magnesium limitation.

  Sulfur insufficiency represents another environmental alteration impacting microalgae development. Sulfur-containing amino acids like cysteine and methionine, along with other significant metabolites, are produced by microalgae. In cases of sulfur deficiency, oxygenic photosynthesis decreases, hydrogenase activation increases, and the formation of microalgal chlorophyll is reduced in C. reinhardtii and C. fusca (44). Conversely, a deficit in sulfur encourages carotenoid synthesis. Notably, nitrogen limitation is not as effective in inducing astaxanthin and lipid accumulation in H. pluvialis as it is in C. reinhardtii and Parachlorella kessleri (45, 46).

IV. APPLICATION OF MICROALGAL PIGMENTS

The presence of pigments within the structure of microalgae significantly influences their observable coloration, a distinctive characteristic. These pigments are chemical compounds with a diverse range of colors and are integral components of the microalgae's photosynthetic machinery (47). Various environmental factors can impact the specific colors exhibited by microalgae, including temperature, radiation, wavelength of light, photoperiod, pH levels, nutrient availability, nitrogen concentration, salinity, exposure to pesticides, and exposure to heavy metals (48). A reliable indicator of carotenoid production in microalgae under the influence of environmental factors is the carotenoid-to-chlorophyll ratio (Car/Chl). This ratio tends to increase in response to combined stresses such as high irradiance and nitrogen deprivation, leading to the accumulation of secondary carotenoids (49).

Microalgae primarily contain three major natural pigments: chlorophylls, carotenoids, and phycobiliproteins. These pigments find extensive applications in various industries, including biomaterials, cosmetics, pharmaceuticals, food coloring, and as ingredients in both human and animal feed (50). They exhibit a wide spectrum of hues, ranging from green to yellow to brown to red. For instance, blue pigments derived from Spirulina are provided by phycocyanins, the yellow pigmentation in Dunaliella is attributed to the presence of β-carotene, and Haematococcus microalgae contribute yellow to red pigments due to the presence of astaxanthin (51). Figure 2 illustrates the primary pigments and their diverse functions. In their study, Rodrigues et al. (52) identified 24 carotenoids, 3 phycobiliproteins, and 2 chlorophylls in the microalga Phormidium autumnale. Among the major pigments present in the biomass were all-trans-carotene (225.44 g g1), all-trans-lutein (117.56 g g1), all-trans-zeaxanthin (88.46 g g1), along with chlorophyll a (2.700 g g1) and C-phycocyanin (2.05 x 105 g g1). In the case of the microalga Coelastrum cf. pseudomicroporum Korshikov, when cultivated in urban wastewater and subjected to salt stress, it accumulated carotenoids ranging from 1.73 to 91.2 picograms per cell.

Microalgal pigments have gained recognition for their potential applications across various industries due to their valuable properties such as anti-inflammatory, neuroprotective, antioxidant, and hepatoprotective effects (2). They are already widely employed in sectors including food, nutraceuticals, pharmaceuticals, aquaculture, and cosmetics. Notable examples of microalgal pigments currently used in these industries include astaxanthin from Haematococcus, β-carotene from Dunaliella, and phycocyanin along with other phycobiliproteins from Arthrospira platensis (50).

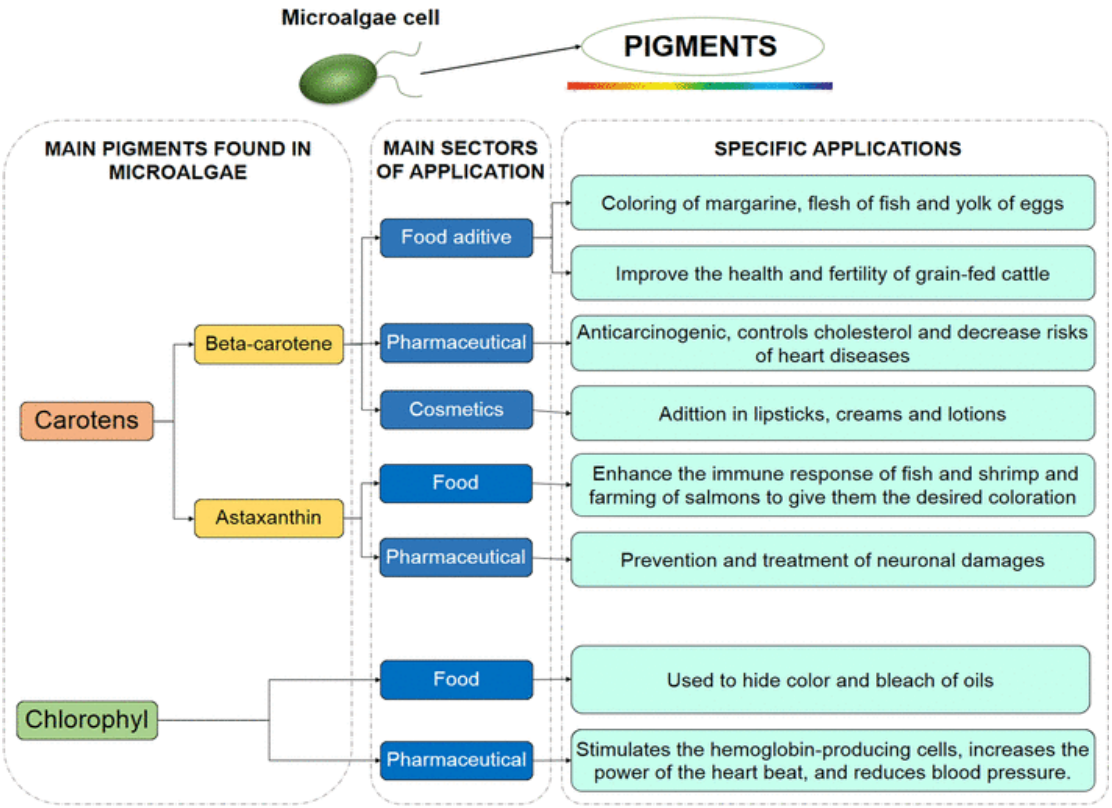

Figure 2: Principal microalgae-derived pigments and their principal uses

1. **Pharmaceutical Use and Prospecting:** Among the various bioactivities associated with microalgae pigments, antioxidant activity stands out as the most well-known. This antioxidant activity may serve as the underlying mechanism for other beneficial bioactivities, such as anti-inflammatory and anti-cancer properties (53). Some examples of phycobiliproteins include allophycocyanin, phycoerythrin, and phycocyanin. Phycocyanin, derived from cyanobacteria, holds significant promise for pharmaceutical applications due to its demonstrated antioxidant, anti-inflammatory, neuroprotective, and hepatoprotective properties. Research has shown that phycocyanin possesses radical scavenging properties, reducing microsomal lipid peroxidation (54). Furthermore, C-phycocyanin produced by Arthrospira platensis has exhibited hypocholesterolemic effects when modeled on serum cholesterol levels (55).

   One specific instance involves a phycocyanin derived from A. platensis, which was reported to inhibit the growth of human leukemia K562 cells (56). Additionally, antitumor activities of phycocyanins have been demonstrated by reducing tumor necrosis factor levels in the blood serum of mice treated with endotoxin. Among the vast array of over 600 carotenoids found in nature, β-carotene holds a prominent position as one of the most significant. Carotenoids, encompassing both xanthophylls and carotenes, are the microalgal pigments that have garnered the most attention due to their various bioactivities. β-Carotene, in particular, plays a pivotal role in supporting human health by aiding in immune enhancement and preventing conditions such as cataracts, night blindness, and skin disorders. Notably, it can be converted into vitamin A, further enhancing its biological functions (57). Astaxanthin, among the xanthophylls, stands out prominently due to its exceptional bioactivity potential. Similar to the other pigments discussed earlier, astaxanthin boasts significant antioxidant capabilities. In fact, it can be regarded as a super vitamin E, as it exhibits 500 times the antioxidant capacity of tocoferol and ten times the antioxidant potential of β-carotene (58). Thanks to its potent bioactive antioxidant properties and its ability to traverse the blood-brain barrier, astaxanthin finds application in preventing neuronal damage associated with conditions like age-related macular degeneration, ischemic reperfusion injury, Alzheimer's and Parkinson's diseases, as well as injuries to the spinal cord and other parts of the central nervous system (32). In vitro research has demonstrated the effectiveness of astaxanthin in inhibiting the oxidation of low-density protein pigments from microalgae, specifically pigment 469. This suggests potential applications in the treatment of conditions such as ischemic brain development, coronary heart disease, and arteriosclerosis (59). Importantly, it's worth noting that astaxanthin exhibits antioxidant activity in both hydrophilic and hydrophobic environments, as reported by Kobayashi and Sakamoto in 1999.

   Moreover, astaxanthin has shown promise in inhibiting the carcinogenicity of aflatoxin and stimulating enzymes responsible for metabolizing xenobiotics in the rat liver (59). In vitro studies have also revealed astaxanthin's immune-stimulatory effect, with modulation of both the humoral and non-humoral immune systems. This results in an increased release of interleukin-1 and tumor necrosis factor in mice (60). Additionally, astaxanthin stimulates the production of T-helper cell antibodies, as well as immunoglobulins A, M, and G (58). A patent has been granted for the development of an oral preparation for the treatment of Helicobacter infections, highlighting astaxanthin's

potential in managing Helicobacter infections in the gastrointestinal tract of mammals (61).

Reynoso-Camacho et al. (2011) conducted research revealing the chemoprotective effects of lutein against colon cancer induced by DMH. Mice fed a diet containing 0.002% lutein demonstrated a prophylactic effect, leading to a 55% and 32% reduction in the number of tumors when administered as a therapy after DMH exposure (61).

2. **Food and Nutraceuticals:** Compounds derived from microalgae with antioxidant properties are particularly enticing for various industrial applications. During industrial food preparation and storage, essential nutrients can degrade and potentially produce harmful compounds. To mitigate these issues, common treatments involve the use of synthetic antioxidants like EDTA, butylated hydroxyanisole (BHA), and butylated hydroxytoluene (BHT) (62). However, some synthetic compounds have been linked to adverse health effects, even though their use is regulated and restricted by legislation (63). As a result, there has been a growing preference for natural colors derived from a variety of sources, making microalgae an eco-friendly and viable alternative. Phycocyanin, a blue pigment from Arthrospira platensis, β-carotene, a yellow pigment from Dunaliella, and astaxanthin, a yellow to red pigment from Haematococcus, are examples of non-toxic and non-carcinogenic natural pigments that are gaining popularity (32).

   Carotenoids from the Dunaliella genus, such as β-carotene, significantly enhance the appearance of products like margarine, fruit juices, cheese, baked goods, canned meals, dairy products, and confectionery items. β-carotene has been recognized as a safe and natural food coloring agent by the US Food and Drug Administration (US FDA). Additionally, β-carotene, being a pro-vitamin A (retinol), is used in the preparation of nutritious foods (2). Arthrospira platensis-derived phycocyanin is currently utilized as a food coloring agent in various products, including confections, jellies, chewing gum, ice cream, popsicles, soft drinks, dairy items, and wasabi (1,2). Furthermore, whole A. platensis and phycocyanin extracts have been incorporated into cookies to enhance protein and fiber content, potentially offering health benefits (64).

3. **Feed:** The color of salmon is of paramount importance in salmon farming, and synthetic astaxanthin is a primary source used to achieve the desired carotenoid coloration. However, as an alternative, carotenoids including canthaxanthin, astaxanthin, and lutein from Chlorella sp. have gained widespread usage. These carotenoids are incorporated as ingredients in the feed for salmonid fish, trout, and poultry to enhance the reddish coloration of fish or the yellow hue of egg yolks (65, 66). Furthermore, astaxanthin has been demonstrated to bolster the resistance of fish and prawns, thereby promoting their overall health and growth (51). It's important to note that the US Food and Drug Administration (US FDA) permits the use of astaxanthin as a colorant additive in fish feed (32). In the context of fish and shellfish farming, carotene-rich feed is provided to enhance their visual appearance (51).

4. **Other Applications:** Phycobiliproteins play a vital role in fluorescence-based detection systems, particularly in flow cytometry, owing to their unique spectral characteristics (67). These properties also make phycocyanin a suitable coloring agent for eyeliners and lipsticks (1). Furthermore, streptavidin-labeled phycoerythrin has found application in the

detection of DNA and protein probes, serving as a secondary color in the labeling of antibodies due to its absorbance spectrum properties (54). For both external and intracellular labeling in flow cytometry, additional low-molecular-weight phycobiliproteins sourced from cryptomonads can be employed (68).

V. MICROALGAE IN COSMETICS AND COSMECEUTICALS

As per the dictionary definition, cosmetics refer to "products intended to be rubbed, poured, sprinkled, or sprayed on, introduced into, or otherwise applied to the human body or any part thereof for the purposes of cleansing, beautifying, enhancing attractiveness, or altering appearance" (69). It's important to note that cosmetics are designed not to interfere with the normal functioning of the human body, in contrast to pharmaceuticals and medications. However, products falling into the category of cosmetics and pharmaceuticals that lack international harmonization are often referred to as "cosmeceuticals" or "over-the-counter" (OTC) products in the United States, and "quasi-drugs" in Japan. The nomenclature debate largely centers on factors such as the concentration of active ingredients, penetration into the stratum corneum, clarification of the mechanism of action, and the presence of clinical trials to support claims (70).

For the purpose of this discussion, the terms "cosmetics" and "cosmeceuticals" will be treated as a single category. Utilizing microalgae in cosmetics/cosmeceuticals is an appealing approach to meet the increasing demand for innovative natural ingredients derived from ecologically sustainable biomass. This is due to the high productivity of microalgae and their ease of extraction under controlled conditions (71). Innovative methods for extracting and purifying microalgae biomass have been developed to harness the potential of these microorganisms in cosmetics, as it is challenging to incorporate the entire biomass into cosmetic formulations.

Extensive scientific research on the biological properties of microalgae extracts or their components, such as specific polysaccharides (72, 73), has led to the development of numerous cosmetic products containing microalgae. These products often incorporate biopeptides to stimulate collagen production and substances like astaxanthin and its esters, known for their potent antioxidant properties in preventing tyrosinase-induced hyperpigmentation (74,75). Consequently, these ingredients can be found in a variety of commercial cosmetic formulations, including sunscreens, emollients, anti-aging and rejuvenating creams, as well as hair care products (76, 77). However, only a limited number of these products are available and sold on a global scale.

Therefore, biopigments derived from microalgae biomass offer appealing alternatives with economic potential. This is due to the rapid growth of microalgae, their high pigment content, a wide range of color variations, and the minimal to nonexistent risk of causing skin allergy reactions (32, 77).

Table 2: Cosmetic products on the market with pigments from microalgae

Cosmetic	Cyanobacteria /microalgae	Pigment	Potential activity	Referance
Pepha®-Ctive	Dunaliella salina	β-Carotene	Antioxidant, stimulates cell proliferation	78
Dermochlorella D®	Chlorella vulgaris	Carotenoids	Photo protection against UV light and oxidative damage, enhances collagen synthesis	79
OceaRides™	Odontella spp.	NI	Stimulates elastin synthesis	80
AstaPure®	Haematococcuspluvialis	Astaxanthin	Antioxidant properties	81
FucoVital™	Phaeodactylumtricornutum	Fucoxanthin	Antioxidant properties	81
Megassane®	Phaeodactylumtricornutum	NI	Cell protection from UV, prevention of photo-aging and age-spots	82
Linablue®	Arthrospira spp.	Phycocyanin	Eye shadow	83

Table 2 provides an overview of the utilization of microalgae pigments in commercial cosmetics. The coloration of biomass is attributed to the natural pigments generated through the photosynthetic processes of microalgae. These photosynthetic pigments are classified into three categories: carotenoids, chlorophylls, and phycobiliproteins. Autotrophic organisms such as plants, algae, and cyanobacteria utilize these pigments to capture solar energy, which is then converted into chemical energy through the process of photosynthesis (84). It is well-documented in specialized literature that controlling environmental conditions during the growth of microalgae can enhance the production of lipids, proteins, and pigments (85, 86, 87, 88).

Safety considerations, specifically toxicological aspects of microalgae pigments, have garnered recent attention. Concerns have arisen regarding the adverse effects of algae on fisheries, aquaculture, and freshwater resources. Algal cells have developed various defense mechanisms and strategies for environmental adaptation, including the production of phycotoxins and metabolites, some of which exhibit biological activities, while others serve different functions (89, 90). Nonetheless, it's important to note that out of the numerous species of microalgae, only around 200 are considered potentially harmful, and approximately 100 of them are believed to have the capacity to produce toxins. The most hazardous genera among microalgae are planktonic and benthic dinoflagellates as well as planktonic diatoms. In rare cases, phytotoxins can prove fatal to humans (90, 91). These toxins can also lead to gastrointestinal, cutaneous, and neurological issues in humans.

Moreover, microalgae and their derivatives may contain cyanotoxins, inorganic arsenic, and heavy metals (92, 93). Regulatory bodies such as the Food and Drug Administration (FDA) and international agencies have established standard criteria to ensure the quality and safety of products derived from microalgae (94). Employing effective extraction techniques can be a valuable strategy for isolating pigments or other components from microalgae while eliminating the presence of harmful phycotoxins or other hazardous residues. Microalgae sourced from aquaculture, which provides a more controlled environment compared to natural sources, can mitigate some of the toxicological risks associated with contamination and bioaccumulation. However, businesses should establish monitoring systems to detect harmful algal species, phycotoxins, and other toxins throughout the production process. Advances in recent years have significantly improved the development of more accurate, sensitive, and rapid methods for identifying various microalgae species and toxins (95).

Furthermore, recent deliberations in the United States, Japan, China, and Europe (96) have revolved around legal and regulatory considerations concerning the commercial use of carotenoids produced from microalgae biomass in food and cosmetic applications. Astaxanthin, -carotene, and chlorophyll derived from specific microalgae species are subject to FDA regulations and approvals due to their non-carcinogenic and safe properties (32). Additionally, astaxanthin obtained from Haematococcus pluvialis has received approval as a coloring agent in Europe, the United States, and Japan. Consequently, the FDA has sanctioned its direct consumption by humans and granted it the "generally recognized as safe (GRAS)" designation (97).

VI. CONCULSION

Major pigments like chlorophyll a, b, and c, astaxanthin, beta-carotene, xanthophylls, and phycobiliproteins have a wide array of intriguing applications in diagnostics, biomedical research, therapies, and coloration in cosmetics, dairy products, and other foods. They are gradually replacing synthetic alternatives due to their safety and absence of carcinogenic potential. The concentration of pigments in microalgae varies depending on the species and growth conditions. The development of pigments in microalgae is influenced by various factors, including temperature, salinity, light intensity, light wavelength, photoperiods, pH levels, nutrient availability, nitrogen supplementation, exposure to pesticides, and exposure to heavy metals. Consequently, when producing microalgal pigments for various applications, it is essential to consider these aforementioned factors. These advantages underscore the broad range of potential applications and value associated with microalgae, some of which have already been successfully implemented on an industrial scale.

Therefore, further research is needed to enhance existing methodologies and explore novel technologies related to microalgae characteristics, pigment properties, and biosynthetic metabolism. To overcome these challenges and establish practical pathways for marketing bioproducts, continuous pursuit of innovative technologies is crucial. Additionally, finding methods for harvesting and characterizing bioproducts with reduced solvent usage and energy consumption is essential to reduce costs and environmental impacts. The insights gained from bibliometric mapping provide a comprehensive assessment of the most frequently investigated topics over the past decade, offering a comprehensive view of current research and emerging trends in microalgae. In order for microalgae to gain a more prominent

presence in the market and accelerate the commercialization of valuable products, each of these aspects should be thoroughly explored.

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