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An in-Depth Examination of Marine Pigments: Origins, Biotechnological Uses, And Environmental Impact

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SUMMARY

The rising global demand for food and healthcare products derived from natural compounds has driven the industrial and scientific sectors to continuously explore natural colorants as alternatives to synthetic dyes. Natural pigments encompass a diverse array of chemical molecules found throughout nature. Recently, there has been a growing interest in marine organisms due to their vast and varied environments, which offer an extensive range of colored compounds with bioactive properties and potential biotechnological applications in industries such as food, pharmaceuticals, cosmetics, and textiles. Over the past two decades, the utilization of marine-derived pigments has increased significantly, as they are recognized as environmentally friendly and healthy options.

INTRODUCTION

The use of synthetic colorants has adverse effects on the environment and human health. Biopigments from marine sources are a sustainable and eco-friendly alternative with various industrial applications. They offer biological properties and diverse applications in industries such as food, feed, nutraceuticals, pharmaceuticals, aquaculture, and cosmetics. Marine pigments are economically significant, with an annual growth rate of 10-15%. The most valuable cultivated marine microorganisms for extracting pigments include Monascus sp., *Saccharina japonica*, and many others. Marine pigments contain bioactive compounds and diverse properties, making them a valuable resource for various industries.

Source of marine natural pigments

Marine organisms are potential and sustainable sources of biopigments that can be utilized in the development of new cosmeceutical, nutraceutical, and pharmaceutical products. Algae, microorganisms, and animals are all sources of biopigments. Algae, for instance, is a major resource for pigments such as chlorophylls, carotenoids, and phycobiliproteins. Additionally, indole derivatives, polyenes, alkaloids, peptides, macrolides, melanins, monascins, and terpenoids can be isolated from algae, fishes, mollusks, sponges, mangroves, seawater, and sediments. These marine pigments exhibit antioxidant, anticancer, antibacterial, antimalarial, antitumor, antiviral, and photoprotective properties, among others. Furthermore, natural pigments from marine animals like fishes and invertebrates are of interest due to their higher nitrogen content. Therefore, the marine environment serves as an important source of natural pigments with diverse biological properties.

Animal sources

Marine animals from tropical environments are usually brightly colored. Pigments from these animals can be found in species that live in shallow and deep-water areas. Marine invertebrates like sea urchins, mollusks, and crustaceans produce natural colors such as quinone, carotenoid, and tetrapyrrole compounds.

Vertebrate sources

Marine vertebrates like whales, dolphins, reptiles, and various fishes can accumulate or produce pigments, with carotenoids being the primary ones. These include carotenes and xanthophylls such as lutein, canthaxanthin, or astaxanthin. While not nutritionally required, carotenoids provide health benefits to these animals, contributing to their coloration for camouflage, photoprotection, and signaling. Astaxanthin, in particular, supports reproductive success by enhancing ovarian development, fertilization, hatching, and larval growth, and improves the immune system. Carotenoids give fishes their colors ranging from pink-red and orange-red to greenish-yellow and yellow. Astaxanthin is the predominant carotenoid, involved in creating vibrant colors in fishes and crustaceans and is

found in significant quantities in species like lobsters, salmons, shrimps, and crayfish. It has three isomers, with one being most common in these animals. Other notable carotenoids include tunaxanthin and doradexanthins, contributing to the bright yellow hues in certain fish species' fins and skin.

Marine invertebrates

Marine invertebrates from tropical waters exhibit a vibrant array of colors due to pigments mainly from mollusks, echinoderms, and crustaceans, influenced by diet, symbiotic relationships, and environmental factors. Some can synthesize carotenoids, found in sponges and other specific species, obtained through feeding or symbiosis. Carotenoids like astaxanthin are industrially extracted from krill and crustacean byproducts, despite challenges such as low content and high storage costs. These pigments, including those in bivalves and echinoderms, contribute to the diverse coloration and play roles in invertebrate physiology, with compounds like tetrapyrrole influencing tissue pigmentation.

Plant sources

Phytoplankton and algae are the main sources of marine plant pigments, including carotenoids, chlorophylls, and phycobiliproteins.

Phytoplankton sources

Phytoplankton pigments are key indicators of biogeochemical processes affecting climate change. The primary pigments in phytoplankton include chlorophyll (a, b, c, chlorophyllide a, pheophorbide a) and carotenes (α-carotene, β-carotene, α-cryptoxanthin/zeinoxanthin, lutein, zeaxanthin, lycopene). Chlorophyll consists of an aromatic tetrapyrrole with a magnesium ion and a hydrocarbon tail. Specifically, chlorophyll a, found in all phytoplankton, has a blue/green color, while chlorophyll b offers a green/yellow tone. Phytoplankton pigments are crucial for identifying community diversity, distinguishing between taxa like diatoms, dinoflagellates (fucoxanthin), haptophytes (19′-hex-fucoxanthin), green algae (chlorophyll b), and cyanobacteria (zeaxanthin).

Seaweeds

Recent research and industrial interest have focused on bioactive compounds from seaweeds, attributed to their beneficial health effects. Particularly notable are their carbohydrates, minerals, and pigments such as carotenoids, phlorotannins, phylopheophylin, fucoxanthin, and chlorophyll c, which demonstrate antioxidant, anti-inflammatory, anticarcinogenic, and neuroprotective properties. Seaweeds are categorized based on the pigments produced, into red (Rhodophyta), brown (Ochrophyta), and green (Chlorophyta) algae. Fucoxanthin, a carotenoid found primarily in brown algae and certain microalgae, along with chlorophyll, found in green and brown algae, are of particular interest for their wide range of health benefits and applications in pharmaceuticals, cosmetics, and food industries. Fucoxanthin has been extensively studied for its beneficial effects, with multiple brown algae species identified as sources. Similarly, chlorophyll a, predominant in the marine environment, and other chlorophylls have shown antidiabetic and anticancer properties. The European Food Safety Authority has approved Chlorophyll a from red seaweeds for use in food processing, reflecting its continuous investigation for various industrial applications.

Applications of marine pigments

Marine pigments are sought after in various industries like food, pharmaceuticals, textiles, and cosmetics for their health benefits such as anticancer, antimicrobial, antioxidant, and cytotoxic activities. They are eco-friendly and biodegradable, making them attractive alternatives to synthetic dyes.

Food industry

In the food industry, marine compounds are used as natural preservatives, pigments, stabilizers, and more, with added health benefits. The shift towards these natural compounds is due to concerns over the safety of synthetic dyes. For example, astaxanthin, riboflavin, lycopene, β-carotene, and phycocyanin are recognized as safe and used for coloring foods like ice cream and beverages. Astaxanthin, a powerful antioxidant, and other microalgae derivatives enhance the nutritional value of foods with high protein, omega-3, and fatty acids content. However, natural pigments are generally more expensive than synthetic colors due to their instability and production costs, despite this, their demand continues to grow due to their health benefits and rising food needs globally.

Pharmaceutical and cosmetic industry

The pharmaceutical and cosmetic industries are increasingly drawn to natural, eco-friendly active ingredients, with a growing demand for "vegan," "cruelty-free," and "organic" products, projected to reach a market of $20.8 billion by 2025. Algae, especially macroalgae, are prime contenders for such ingredients due to their beneficial compounds and easy cultivation. Notably, brown algae extracts are commonly used in sensitive skin cosmetics. Compounds like fucoxanthin from brown algae and astaxanthin from Haematococcus pluvialis are studied for their strong antioxidant properties and skin health benefits, including UV protection and anti-inflammatory effects. These marine-derived ingredients are promising for improving sensitive skin health and cosmetic formulations.

Trends and challenges in the use of marine pigments in industry

Marine biopigments are emerging as a valuable source of natural colorants across industries such as food, cosmetics, and pharmaceuticals, with their market expected to grow significantly by 2030. They are preferable for their biological benefits and the trend towards functional products. Algae, bacteria, and yeasts are key sources due to their high yield and biodiversity. However, commercial use faces challenges like production costs and regulatory hurdles. Eco-friendly extraction techniques and the use of waste as culture media are being explored to enhance sustainability and cost-effectiveness. Natural astaxanthin, noted for its higher antioxidant activity, showcases the growing preference for natural over synthetic pigments.

CONCLUSION

Marine biopigments are promising colorants for various industries, including food, pharmaceutical, and cosmetics, due to their biological activities and market demand, with a projected growth in functional products to US$586.1 billion by 2030. The coloring agents market is expected to reach US$86.9 billion by 2030, with natural astaxanthin, valued more for its antioxidant properties, estimated at a market of US$3.4 billion by 2027. However, high production costs, regulatory challenges, and environmental sensitivities limit commercial usage, with examples like Linablue Spirulina Extract. Algae, bacteria, and yeasts are key sources for biopigments, offering high yields and diversity under optimized cultivation conditions. Efficient pigment extraction involves overcoming cell wall resistance and adopting eco-friendly techniques to maximize recovery. For example, treating Chlorella vulgaris with hydrochloric acid enhanced carotenoid yields. Utilizing waste as cultivation media, like cassava for prodigiosin production, fosters a circular economy approach, reducing environmental impacts.

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