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Advances in the Research of Natural Pigments

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ABSTRACT

Natural pigments, derived from plants, animals, microorganisms, and minerals, have garnered significant attention across industries such as food, pharmaceuticals, cosmetics, and textiles due to their eco-friendly, safe, and biologically active properties. This review provides a comprehensive overview of the major types, bioactivities, extraction techniques, applications, and strategies for enhancing the stability of natural pigments. It examines the chemical characteristics and biosynthetic pathways of key pigments, highlighting their health-promoting effects, including antioxidant and anti-inflammatory activities. The review compares conventional extraction methods with modern green extraction technologies, while also introducing innovative approaches such as microbial fermentation and synthetic biology in pigment production. Current industrial applications of natural pigments are discussed in detail, along with advanced techniques—such as microencapsulation, complex formation, and structural modification—employed to improve pigment stability. Finally, the review outlines existing challenges and future prospects in natural pigment research, offering a theoretical foundation for further exploration and practical utilization..

KEYWORDS

Natural pigments; Extraction; Synthetic biology

1 Introduction

Pigments, substances capable of imparting color to materials, are widely used in various aspects of human life, including food, cosmetics, pharmaceuticals, and textiles. Synthetic pigments dominate the market due to their bright hues, strong coloring power, chemical stability, and low cost. However, studies have shown that certain synthetic pigments may pose risks to human health. In cosmetics, these artificial colors can trigger allergic reactions, skin discoloration, flushing, rashes, and other adverse effects. Such findings have led both consumers and manufacturers to shift attention back to natural pigments. Derived primarily from plants, animals, microorganisms, and minerals, natural pigments can be broadly classified into water-soluble and fat-soluble types based on their solubility. Compared to synthetic alternatives, natural pigments offer advantages such as safety, eco-friendliness, and biodegradability, while often providing nutritional benefits and promoting well-being. Many natural pigments not only serve as colorants but also exhibit biological activities, including antioxidant, antimicrobial, and anti-inflammatory properties [1]. This article aims to provide a comprehensive overview of the latest advances in natural pigments, systematically reviewing their types and characteristics, biological activities, extraction techniques, applications, and strategies for improving stability, while also offering insights into future development directions, serving as a reference for researchers and industry professionals in related fields.

2 Main types and characteristics

2.1 Carotenoids

Carotenoids are a significant group of natural pigments, with over 300 identified types. They display a range of colors, including yellow, orange, red, and purple, and are widely distributed in the roots, leaves, flowers, and fruits of plants. Certain microorganisms are also capable of synthesizing carotenoids. Structurally, these pigments are characterized by a conjugated polyene chain composed of multiple isoprene units. Depending on the functional groups at their terminal ends, carotenoids can be classified into hydrocarbons (e.g., alpha-carotene, beta-carotene, gamma-carotene), alcohols (e. g., lutein), ketones (e.g., capsanthin, capsorubin, astaxanthin, and canthaxanthin), and acids (e.g., crocetin, carminic acid, and bixin). Carotenoids are generally lipid-soluble, exhibit good thermal stability, and are relatively unaffected by pH changes. However, they are sensitive to light and oxygen and can be easily degraded by enzymes, leading to color fading. Lycopene stands out as the most potent antioxidant among carotenoids, offering benefits such as anti-aging effects, UV protection, cancer prevention, inhibition of atherosclerosis, and the reduction of cataract risk [2].

2.2 Anthocyanins

Anthocyanins typically occur in combination with sugars as glycosides, also known as anthocyanidins. These pigments are widely sourced from natural materials such as grapes, raspberries, strawberries, apples, cherries, red cabbage, and eggplant skins. They exhibit a range of colors including blue, red, yellow, and purple, are mostly water-soluble, and their hues are highly sensitive to environmental factors like pH. Black rice pigment is a representative example of anthocyanins, valued not only for its coloring properties but also for its ability to scavenge free radicals, delay aging, support cardiovascular health, and help prevent iron-deficiency anemia [3].

2.3 Flavonoid pigments

The core structure of flavonoid pigments is based on 2-phenylbenzopyranone. Over 400 different flavonoid pigments have been identified. These compounds exhibit acidic properties due to the presence of multiple hydroxyl groups, making them soluble in alkaline solutions. At the same time, the oxygen atom in their heterocyclic ring imparts weak basic characteristics, allowing them to react with certain strong inorganic acids and produce distinctive colors [4].

2.4 Pyrrole-based pigments

Pyrrole-based pigments are derivatives formed by four connected pyrrole rings, including chlorophyll, heme, bilirubin, and phycocyanin. Chlorophyll is widely present in the chloroplasts of green plants and is relatively stable. Heme is the red pigment found in the blood and muscles of higher animals. Bilirubin is a reddish-brown pigment primarily located in the animal liver, while phycocyanin is the blue pigment found in blue-green algae [5].

2.5 Quinone pigments

Quinone pigments are derivatives of quinones and include benzoquinones, naphthoquinones, anthraquinones, and phenanthraquinones. Benzoquinone pigments are mostly yellow in color, while notable naphthoquinone pigments include shikonin. Anthraquinone pigments encompass alizarin, emodin, carmine, and lac dye. Most quinone pigments are lipid-soluble and exhibit good stability to light and heat under acidic conditions. Capsanthin, a representative quinone pigment, is widely used for coloring in pharmaceuticals, food, and cosmetics due to its vibrant hue and excellent resistance to light, heat, acids, alkalis, and oxidation [6].

3 Biological activity and health benefits

3.1 Antioxidant properties

Numerous natural pigments exhibit remarkable antioxidant effects. By effectively neutralizing free radicals, they help reduce oxidative damage, thereby supporting cellular health and slowing the aging process. For instance, astaxanthin is a powerful natural antioxidant with a capacity far surpassing that of vitamin E. It efficiently scavenges free radicals, shields cells from oxidative stress, and contributes to anti-aging benefits [7].

3.2 Anti-inflammatory and immunomodulatory effects

Certain natural pigments demonstrate notable anti-inflammatory and immunomodulatory properties. Prodigiosin, derived from marine sources, can suppress the secretion of the inflammatory cytokine IL-6 by modulating the NF-κB pathway. Fucoxanthin activates the UCP1 protein, promoting the browning of white adipose tissue, which contributes to the prevention and management of obesity and related metabolic disorders. Nuszkiewicz et al. found that anthocyanins interact with key signaling pathways such as Nrf2 and NF-κB, a mechanism closely linked to the prevention of chronic diseases and recovery after physical exertion [8].

4 Extraction and Preparation Techniques

4.1 Extraction methods

Solvent extraction remains the most conventional approach, in which suitable solvents are selected based on the solubility of pigments. Modern green extraction techniques include supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction, and enzymatic extraction. These advanced methods offer significant advantages such as higher extraction efficiency, reduced environmental impact, and improved product purity.

4.2 Microbial fermentation

Compared to extracting pigments from plants and animals, microbial fermentation for natural pigment production is independent of seasonal and geographical constraints. Certain microorganisms naturally produce pigments. For instance, Sphingomonas species can synthesize carotenoids, while *Rhodotorula* yeast is capable of producing red pigments and astaxanthin.

4.3 Synthetic biology approaches

Synthetic biology has opened new avenues for the production of natural pigments. By leveraging genetic engineering to modify microorganisms or plants, natural pigments can be efficiently biosynthesized as sustainable alternatives to synthetic dyes. Carminic acid, a highly valued natural pigment, has been successfully produced through engineered pathways. Yang et al. constructed a biosynthetic pathway for carminic acid in Escherichia coli, enabling direct production from glucose and achieving a titer of 0.63 ± 0.02 mg/L [9].

5 Applications

Natural pigments are widely used in industries such as food, pharmaceuticals, cosmetics, and textiles. In the food industry, they are primarily employed to enhance the visual appeal of products by providing natural coloration. In pharmaceuticals and health supplements, natural pigments not only improve appearance but also contribute bioactive properties—such as antioxidant, anti-inflammatory, antimicrobial, and anticancer effects. In cosmetics, their mildness and safety have led to growing interest. Compared to synthetic dyes, natural pigments are less likely to cause skin irritation or allergic reactions and often offer additional skincare benefits. They are also increasingly applied in textile dyeing and other industrial areas. For instance, pigments derived from gromwell (Lithospermum erythrorhizon) can produce vibrant hues in fabrics. Additionally, natural pigments serve as safe, non-toxic coloring agents in products like toys and stationery.

6 Strategies for enhancing stability

The stability of natural pigments can be improved through chemical or enzymatic modification of their molecular structure. Microencapsulation is another effective approach, where pigment molecules are enclosed within protective coating materials to shield them from detrimental factors such as light, oxygen, and heat. For example, İncegül et al. successfully enhanced the stability and bioactivity of anthocyanins using microencapsulation techniques [10].

7 Challenges and solutions

Despite significant progress in the study of natural pigments, several challenges remain to be addressed. One major issue is the stability of natural pigments. Many of these pigments are highly sensitive to light, heat, oxygen, and pH changes, making them prone to fading or degradation, which limits their practical applications. In addition, the extraction and purification processes for natural pigments are often costly, putting them at a disadvantage compared to synthetic alternatives. To overcome these limitations, future research should focus on the application of innovative technologies and the development of novel products. In terms of technological advancement, synthetic biology offers promising tools and approaches for more efficient pigment production. Regarding product development, there is a growing need to design multifunctional natural pigments that not only provide color but also deliver bioactive benefits, aligning with consumer demand for healthier and more functional products.

8 Conclusion

As an eco-friendly alternative to synthetic dyes, natural pigments hold immense potential across industries such as food, pharmaceuticals, cosmetics, and textiles. This paper has provided a comprehensive overview of the main categories of natural pigments, their bioactive properties, extraction techniques, application areas, and strategies for enhancing stability. While natural pigments offer numerous advantages, challenges such as poor stability and high production costs still persist. Future efforts should prioritize the development of advanced technologies and innovative product designs. With the rising consumer preference for "green, sustainable" and "additive-free" products, the market outlook for natural pigments is increasingly promising.

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