Respobio Journal: Postharvest and Biotechnology in Food, 2026; 2 (1): 48–59 OPEN ACCESS

e-ISSN : 2621-9468

Review

The utilization of natural pigments from agricultural crops via fermentation as functional food colorants: a review

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Abstract

Growing consumer awareness regarding food safety and health has intensified the demand for natural alternatives to synthetic food colorants, which are associated with potential adverse health effects and strict regulatory limitations. Tropical agricultural commodities offer abundant and diverse sources of natural pigments, including anthocyanins, carotenoids, chlorophylls, and betalains, which also exhibit functional bioactivities such as antioxidant and antimicrobial properties. However, challenges related to pigment stability, bioavailability, and efficient utilization of agro-industrial waste remain significant. This review aims to evaluate the potential of natural pigments derived from tropical agricultural commodities and their enhancement through fermentation processes for application as functional food colorants. The study was conducted through a comprehensive literature review of recent scientific publications focusing on pigment classification, sources, biochemical characteristics, and fermentation-based improvement strategies. The findings indicate that fermentation using microorganisms such as bacteria, yeasts, and molds plays a crucial role in modifying pigment structure, enhancing stability under various environmental conditions, and increasing biological activity through enzymatic bioconversion. Furthermore, the utilization of tropical agro-waste materials, including fruit peels and processing residues, provides an opportunity for sustainable pigment production while supporting waste valorization. Fermentation also contributes to improved pigment extractability and functionality, making it suitable for incorporation into food systems. Overall, the integration of tropical agricultural resources with fermentation technology presents a promising approach to develop safe, sustainable, and functional natural food colorants. Future research is needed to optimize fermentation conditions and scale up production processes for industrial applications.

Article History
Received October 29, 2025
Accepted April 28, 2026
Published May 23, 2026

Keywords
Natural Pigments, Fermentation, Food Colorants, Tropical Agricultural Commodities.

1. Introduction

The global food industry is currently facing increasing pressure to reduce the use of synthetic additives, particularly food colorings, which are often used to enhance the visual appeal of products (1). The use of synthetic food colorings such as tartrazine, erythrosine, and allura red has been linked to various health effects, including allergic reactions, hyperactivity in children, and potential carcinogenic effects from long-term exposure. This issue has become a serious global concern, prompting many countries to tighten regulations, including restrictions on the types of substances allowed and mandatory labeling requirements for food products (2). As global consumer awareness of food safety, quality, and healthy lifestyles continues to grow, demand for clean-label products has surged (3).

The development of natural dyes is one of the most common approaches taken to address this need. Natural pigments derived from biological sources not only serve as

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ISSN 2621-9468 online, DOI 10.20956/Respobio.v2i1.2295

colorants but also possess biological activities such as antioxidant, antimicrobial, and anti-inflammatory properties (4). Tropical agricultural commodities hold great potential as a source of natural pigments due to their abundant availability and high content of bioactive compounds, including in byproducts and agro industrial waste that have not yet been fully utilized (5). In recent years, fermentation technology has been developed as a strategy to improve the efficiency of pigment production, as it can enhance stability, increase bioavailability, and boost the functional activity of pigment compounds (6). Some examples of materials with potential for use include purple sweet potatoes, dragon fruit peels, mangosteen peels, cocoa waste, coffee husks, and sugarcane bagasse, which have not yet been fully utilized. This potential opens up opportunities for the development of food colorants based on local resources that are not only safer but also offer functional and economic added value (6).

Several review articles have published studies on the production and utilization of natural pigments in the food industry. The results of these studies indicate that microbial fermentation can increase pigment productivity, optimize biosynthetic pathways, and improve stability and biological activity under various food processing conditions (7–9). Other studies have also shown that plant-based commodities, including those from tropical regions, contain bioactive pigments that have the potential to be used as functional food ingredients (9,10). However, to date, there has been no review article specifically examining the use of tropical agricultural commodities and waste as substrates in the production of pigments through integrated fermentation. The relationship between the type of material, substrate characteristics, fermentation conditions, and the quality of the resulting pigments in food systems has not been comprehensively discussed in a single study. This situation indicates that the development of fermentation-based pigment production using tropical commodities lacks a solid foundation. Therefore, this review article aims to examine the potential for producing natural pigments from tropical agricultural commodities through fermentation, evaluate their stability and functional activity, and identify opportunities for their development as sustainable functional food colorants.

2. Classification, sources, and characterization of natural pigments

2.1. Classification of natural pigments based on chemical structure and source

Natural pigments are organic compounds that absorb light at specific wavelengths, thereby producing specific colors that can be seen with the naked eye (11). In the food industry, natural pigments not only serve as colorants but also offer added value as bioactive components with the potential to provide health benefits (12). Based on their chemical structure, biological origin, and physicochemical properties, natural pigments can be grouped into several main categories, each with distinct characteristics and stability. This classification is important for understanding the potential applications of each pigment, particularly in the development of functional food colorants. Additionally, the characteristics of each pigment also determine its response to processing methods, including fermentation, which can affect its stability and bioactivity (12).

2.1.1. Anthocyanins

Anthocyanins are a group of water-soluble flavonoid compounds that contribute to the red, purple, and blue colors found in various plant parts, such as fruits, flowers, and tubers (13). The basic structure of anthocyanins is a flavilium cation (2-phenylbenzopyrilium) composed of a C6–C3–C6 carbon skeleton, with variations in hydroxyl and methoxyl substituents that affect the intensity and stability of the color (14). In plant tissues, anthocyanins are generally found in a sugar-bound form as anthocyanin glycosides, while the unsugarated form is known as anthocyanidin. These structural variations result in differences in solubility, stability, and response to environmental factors such as pH, temperature, light, and oxygen (15). Under acidic conditions (pH < 6), anthocyanins tend to be red, whereas at neutral to alkaline pH levels, their color can change to purple or blue (16). In tropical regions, abundant sources of anthocyanins include purple sweet potatoes (*Ipomoea batatas*), white mulberries (*Morus alba*), purple eggplants (*Solanum melongena*), and various local berries (17). In addition to serving as a natural colorant, anthocyanins are also known for their high antioxidant activity, making them a promising key component in the development of functional foods. However, anthocyanins are relatively unstable, so technologies such as fermentation are needed to preserve their quality during processing and storage (18).

2.1.2. Carotenoids

Carotenoids are a group of lipophilic pigments that are insoluble in water and are responsible for the yellow, orange, and red colors found in various foods, particularly fruits and vegetables (19). Structurally, carotenoids consist of a polyisoprenoid chain with a system of conjugated double bonds that play a role in light absorption and antioxidant activity. Based on their composition, carotenoids are divided into two main groups: carotenes, which consist solely of carbon and hydrogen atoms, and xanthophylls, which contain oxygen atoms in the form of hydroxyl or carbonyl groups (20). Sources of carotenoids in tropical regions are highly diverse, including mangoes, papayas, yellow squash, and jackfruit, which contain compounds such as β-carotene, lutein, and lycopene. In addition, certain microalgae and marine organisms are also potential sources of carotenoids, particularly for compounds such as astaxanthin (21). Carotenoids are relatively more stable than other pigments under neutral to slightly acidic pH conditions, but they remain susceptible to degradation caused by oxidation, light exposure, and high temperatures. Functionally, carotenoids play a vital role in health, particularly as provitamin A, as protectors of cells against oxidative stress, and in maintaining eye and cardiovascular health (22). Therefore, carotenoids have great potential as both natural colorants and bioactive components in functional foods.

2.1.3. Chlorophyll and its derivatives

Chlorophyll is the primary green pigment in plants and plays a crucial role in photosynthesis, particularly in the absorption of light energy. The structure of chlorophyll consists of a porphyrin ring that binds a magnesium ion (Mg^{2+}) at its center, as well as a phytol chain that imparts hydrophobic properties to the molecule (23). Chlorophyll is generally classified into chlorophyll a and chlorophyll b, which have minor differences in their substituent groups but affect the light absorption spectrum (24). During food processing, particularly under acidic conditions and at high temperatures, chlorophyll can degrade through the release of magnesium ions, forming pheophytin, which causes the color to turn brownish-green. This change poses a challenge to the use of chlorophyll as a natural colorant, as it can reduce the visual quality of food products (25). Nevertheless, some chlorophyll derivatives, such as chlorophyllin and chlorophyllide, exhibit greater stability and have been used in certain food applications. In addition to serving as colorants, chlorophyll and its derivatives also hold potential as bioactive compounds with antioxidant activity. With proper processing, chlorophyll can still be utilized in the development of food products that emphasize natural and functional concepts (26).

2.1.4. Betalain

Betalains are a group of water-soluble pigments that give certain plants red to purple (betacyanin) and yellow to orange (betaxanthins) colors (27). Unlike anthocyanins, betalains are found only in the order Caryophyllales and are never present alongside anthocyanins in the same plant. The structure of betalains derives from betalamic acid, which binds to various compounds, resulting in distinctive and relatively stable color variations across a wider pH range (28). Common sources of betalains in tropical regions include red dragon fruit (*Hylocereus spp*.) and beets, which are widely used as natural colorants in food products (29). Compared to anthocyanins, betalains are more stable under varying pH conditions, but remain sensitive to high temperatures and light. In addition to serving as natural colorants, betalains also possess antioxidant activity and anti-inflammatory potential, which support their use in functional foods (28). Therefore, betalains represent an important alternative in the diversification of natural pigments, particularly in the development of products based on tropical commodities. The sources and classification of natural pigments from Indonesia's tropical agricultural commodities are shown in Figure 1.

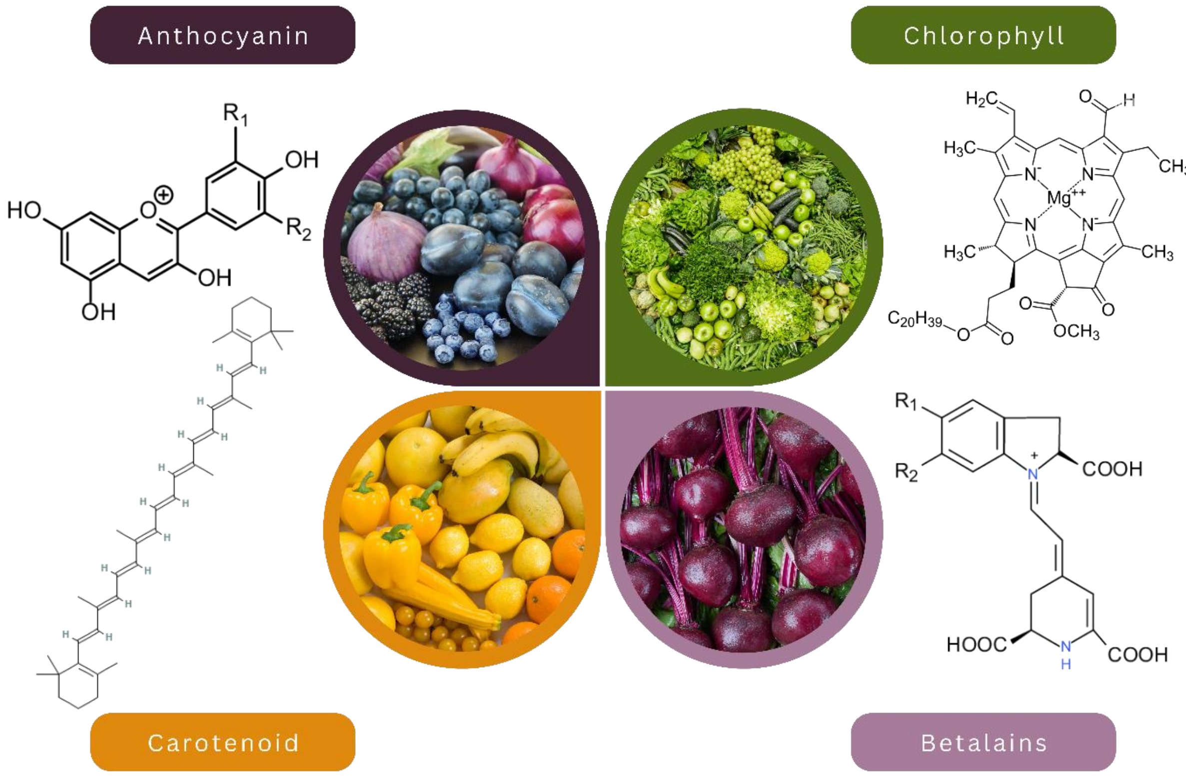

Figure 1. Color pigments in agricultural products and their chemical structure.

2.2. Indonesian tropical agricultural commodities as a source of pigments

Indonesia is a tropical country with exceptionally high biodiversity, giving it great potential as a source of natural pigments derived from various agricultural commodities. Favorable agroclimatic conditions enable the sustainable year-round production of raw materials, both from primary crops and agricultural byproducts. In addition to serving as natural colorants, many of these commodities also contain bioactive compounds that contribute to the functional properties of food, such as antioxidant and antimicrobial activity (30). However, the utilization of these resources remains suboptimal, particularly in terms of extraction and processing into high-value-added products. Technological development, including fermentation, offers a promising approach to enhancing the stability, bioavailability, and economic value of natural pigments derived from tropical commodities. Consequently, the identification and utilization of local commodities represent a strategic step in supporting the development of functional food colorants based on natural resources (31).

2.2.1. Purple Sweet Potato (*Ipomoea batatas* L.)

Purple sweet potatoes are one of Indonesia's high-potential agricultural commodities as a natural source of anthocyanins. This crop is widely cultivated across various regions, ensuring a relatively abundant and sustainable supply of raw materials. The anthocyanin content in purple sweet potatoes is quite high and varies depending on the variety, environmental conditions, and the degree of ripeness at harvest (32). In general, the anthocyanin composition is dominated by cyanidin and peonidin derivatives in the form of glycosides, which contribute to the intense purple color and significant antioxidant activity. In addition, purple sweet potatoes also contain other phenolic compounds that support their functional properties. Despite their great potential, their use as a source of natural pigments remains limited because they are primarily used as fresh food or in simple processed products. The development of extraction and fermentation processes could serve as an effective strategy to enhance pigment stability and the value of the resulting products (33).

2.2.2. Dragon fruit (*Hylocereus* spp.)

Dragon fruit is a rapidly growing tropical horticultural crop in Indonesia and holds potential as a source of natural pigments. The primary pigment in red dragon fruit is betalain, specifically betacyanin, which imparts its characteristic red to purple color. This pigment is water-soluble and exhibits relatively good stability under certain pH conditions, making it a potential natural colorant for various food products. In addition to being present in the fruit flesh, high pigment content is also found in the fruit peel, which has largely remained underutilized to date (34). In fact, dragon fruit peel contains significant bioactive compounds and can be further processed into value-added products. Utilizing peel waste through fermentation and extraction processes can increase the availability of active compounds and improve the efficiency of material utilization. As a result, dragon fruit serves not only as a food commodity but also as a sustainable source of natural pigments (35).

2.2.3. Mangosteen peel (*Garcinia mangostana L.*)

Mangosteen peel is an agricultural byproduct with great potential as a source of natural pigments and bioactive compounds. This part contains various phenolic compounds, such as xanthones, anthocyanins, and tannins, which contribute to its color and high biological activity. The anthocyanins in mangosteen peel are generally cyanidin derivatives that impart a purplish-red color, while xanthones are distinctive compounds with strong antioxidant and antimicrobial activity (36). The use of mangosteen peel remains relatively limited, despite extensive research into its potential as a source of natural extracts. Processing methods such as fermentation can enhance the availability and stability of active compounds through the biochemical transformations that occur during the process (37). Thus, the use of mangosteen peel as a source of natural pigments not only reduces waste but also adds value to the development of functional foods.

2.2.4. Cocoa waste (cocoa by-products)

The cocoa industry produces various byproducts that have the potential to be utilized as sources of pigments and bioactive compounds. Waste materials such as cocoa fruit peel, seed coat, and pulp contain polyphenolic compounds, including catechins and epicatechins, which contribute to the formation of brown color and antioxidant activity. These compounds also play a role in the sensory characteristics of cocoa products, thus possessing important functional value. Currently, most cocoa waste is not yet optimally utilized and often poses an environmental problem (38). Through the fermentation process, the bioactive components in cocoa waste can undergo changes that enhance their biological activity and their potential for use as food additives. This approach opens up opportunities to transform waste into high-value materials for the food industry. With proper management, cocoa waste can serve as a sustainable source of natural pigments while supporting the concept of a circular economy (39).

2.2.5. Coffee waste (coffee by-products)

Coffee waste, such as fruit peel and parchment, is a byproduct of the coffee processing industry, which is quite substantial in Indonesia. This material contains various phenolic compounds, including chlorogenic acid and its derivatives, which contribute to antioxidant activity and natural coloring potential. Additionally, the natural fermentation process that occurs during coffee processing also influences the chemical characteristics and color of this waste. The utilization of coffee waste is currently limited and often causes environmental impacts if not properly managed (40). Further processing through controlled fermentation can enhance the value of coffee waste, both as a source of pigments and as a functional ingredient. This approach aligns with efforts to develop a sustainability-based industry and to utilize resources efficiently. Thus, coffee waste holds great potential to be developed as an innovative raw material in the food industry (41).

2.3. Indonesian tropical agricultural commodities as a source of pigments

Various tropical agricultural commodities, whether primary raw materials or agro-industrial byproducts, show significant potential as sources of natural pigments. Purple sweet potatoes, dragon fruit, mangosteen peel, cocoa waste, and coffee waste contain pigment compounds such as anthocyanins, betalains, and phenolic compounds that not only serve as colorants but also possess biological activities such as antioxidant properties. However, the utilization of these commodities still faces various challenges, particularly regarding pigment stability against environmental factors such as pH, temperature, and oxidation. Therefore, a technological approach is needed to improve pigment quality and stability, one of which is through fermentation processes (42). Thus, fermentation is a key strategy for optimizing the use of tropical crops as a source of functional food colorants.

3. Fermentation in the Production of Natural Pigments

Fermentation is a biotechnological approach that plays a key role in enhancing the quality and functional value of natural pigments. This process involves the activity of microorganisms such as bacteria, molds, and yeasts, which produce enzymes to convert complex compounds into simpler, more stable, and bioactive forms. In the context of natural pigments, fermentation serves not only in production but also in modifying the chemical structure of pigments, thereby enhancing their color intensity, stability, and biological activity (43). Color pigments produce from tropical raw material by fermentation can be seen in Tabel 1.

Table 1. Color pigments produced through the fermentation of agricultural products.

No.	Tropical Commodities	Producing Microorganisms	Fermentation Methods	Pigments Produced	Applications & Functional Uses	Ref.
1	Wheat bran, rice bran, fruit peels, molasses	*Monascus purpureus, Monascus ruber*	Submerged / Solid-State	Red, orange, and yellow pigments (azaphilone)	Stable food coloring, antioxidant	(43)
2	Soybean dreg	*Serratia marcescens*	Solid-State	Prodigiosin (red)	Antibacterial, food coloring, stable	(44)
3	Orange peel waste, pineapple waste, pomegranate waste	*Bacillus safensis, Monascus purpureus*	Submerged & shake-flask fermentation	Red and yellow pigments	Natural food coloring	(44)
4	Dairy sludge, whey	Monascus purpureus, various bacteria	Submerged	Red pigment	Food coloring, biomass enhancement	(44)
5	Rice husk, rice straw	*Monascus spp.*	Submerged	Red and yellow pigments	An alternative to synthetic dyes	(44)
6	Apple pomace	*Sarcina sp., Chromobacterium sp., Micrococcus sp.*	Solid-State	Carotenoids	Food coloring, antioxidants	(44)

Microorganisms play a key role in the fermentation process through the production of enzymes capable of catalyzing various biochemical reactions. Molds such as *Monascus* are known to produce natural red, orange, and yellow pigments that have been utilized in the food industry. Additionally, lactic acid bacteria such as *Lactobacillus* and yeasts such as Saccharomyces cerevisiae play a role in increasing the availability of phenolic compounds and pigments through enzymatic activities, such as β-glucosidase, which can break down glycosidic bonds into more stable and easily absorbed aglycone forms (45).

During the fermentation process, various biochemical reactions occur that affect pigment characteristics. Enzymes produced by microorganisms can hydrolyze complex compounds, modify pigment structures, and enhance their solubility and stability. Additionally, fermentation generally leads to a decrease in pH, which can enhance the stability of certain pigments, such as anthocyanins, under acidic conditions. This bioconversion process also contributes to the formation of derivative compounds with higher antioxidant activity compared to their original forms (46).

Fermentation can enhance the stability of pigments against environmental factors such as temperature, light, and oxidation. In anthocyanin pigments, fermentation can help maintain color intensity by forming more stable structures. Additionally, the antioxidant and antimicrobial activity of natural pigments can also increase due to the transformation of compounds during fermentation. However, the effectiveness of this process is highly influenced by the type of microorganisms, fermentation conditions, and the characteristics of the raw materials used (14).

The application of fermentation to various tropical crops shows significant potential. Fermentation of purple sweet potatoes has been reported to enhance the stability and intensity of anthocyanin color. In dragon fruit peel, the fermentation process increases the extraction and antioxidant activity of betacyanin pigments. Meanwhile, fermented cocoa and coffee waste shows an increase in phenolic compound content, which contributes to color and functional properties. The use of agro-industrial waste as a fermentation substrate also provides added value and supports the concept of sustainability in the food industry (17).

4. Conclusions

Natural pigments derived from tropical agricultural commodities hold great potential as safe and sustainable functional food colorants. Various sources, such as purple sweet potatoes, dragon fruit, mangosteen peel, and cocoa and coffee waste, contain bioactive pigment compounds that not only provide color but also possess beneficial biological activities. Fermentation plays a crucial role in enhancing pigment quality through bioconversion mechanisms that improve stability, bioavailability, and functional activity. Thus, integrating tropical agricultural resources with fermentation technology represents a promising strategy for developing functional food-based natural colorants. Further research is needed to optimize these processes and support their application at an industrial scale.

Acknowledgements

Not Available

Author Contributions

Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing original draft, preparation, review, and editing, visualization: Y.B.B.

Funding

Not Available

Institutional Review Board Statement

Not Available

Data Availability Statement

Not Available

Conflicts of Interest

Not Available

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