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Effect of the Chemical Stability of Betalains and Anthocyanins as Colorants in Cosmetic Formulations

Review Article

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Abstract:
The use of natural pigments as color correctors in cosmetics is on the rise as demand for safe and sustainable ingredients grows. This article examines the chemical stability (pH, temperature, light) that affects the oxidation and degradation of betalains in beets and dragon fruit, and anthocyanins in blackcurrants, mangosteen peel, and black rice. Review methods involved a literature review of journal articles from the past 10 years, focusing on stability with respect to pH, temperature, light, and the chemical structure of the pigments, using Google Scholar, ScienceDirect, Wiley Online Library, and PubMed. The results show that betalains from beets and dragon fruit have high color intensity and strong antioxidant activity but are sensitive to high temperatures and UV light. Anthocyanins from blackcurrants, mangosteen peel, and black rice are more stable at acidic pH levels but degrade at neutral–alkaline pH levels, high temperatures, and under light exposure. It is concluded that natural pigments have potential as cosmetic colorants but require stabilization techniques such as encapsulation and pH adjustment.

INTRODUCTION

Corrigen colorist is part from excipients in the form of substance the dye used in formulation pharmacy or cosmetics For repair or give color on the preparation , with objective increase appearance , identification , and reception consumer to product (Vigneshwaran et al., 2023) . The use of natural pigments from plants as colorants in cosmetic preparations has increased significantly in the last decade, along with the shift in consumer preferences towards safer, more sustainable, and natural-based products. The clean beauty and green cosmetics trends encourage the industry to replace synthetic dyes with natural pigment sources that have better safety profiles, biodegradable properties , and added biological value such as antioxidant and photoprotective activities (Enaru et al., 2021), (Barygina et al., 2019). In the context of skin and hair care, natural pigments not only function as colorants, but also have the potential to provide protective effects against oxidative stress that contributes to skin aging and hair damage due to exposure to UV rays and pollution.

Some potential natural pigment sources as coloristic co-products in cosmetics include beetroot (Beta vulgaris) which is rich in betalains, as well as blackcurrant (Ribes nigrum), red dragon fruit (Hylocereus polyrhizus), black rice (Oryza sativa L.), and mangosteen peel (Garcinia mangostana) which are the main sources of anthocyanins and other pigmented phenolic compounds. Betalains produce bright red to purple colors through the betacyanin and betaxanthin structures, while anthocyanins provide a red-purple-blue color spectrum that depends on the environmental pH (Enaru et al., 2021), (Del Fresno et al., 2019). In decorative cosmetic applications such as lipstick , lip tint , blush on , and semi-permanent hair coloring products, these natural color characteristics are attractive because they provide a soft and natural aesthetic appearance.

In addition to their aesthetic function, these pigments are known to possess relevant biological activities in skincare and haircare preparations . Anthocyanins and betalains exhibit strong antioxidant activity, free radical scavenging ability, and anti-inflammatory potential that supports skin protection from oxidative stress and photodamage (Barygina et al., 2019), (Smeriglio et al., 2016) . Mangosteen peel, for example, contains not only anthocyanins but also xanthones that contribute to color stability and additional biological activities. Similarly, black rice and blackcurrant extracts are reported to contain delphinidin and cyanidin that play a role in collagen protection and inhibiting extracellular matrix degradation.

However, the main challenge in utilizing natural pigments as cosmetic colorants lies in the stability of their chemical structures that act as chromophores in producing color. Betalains have a chromophore system that is susceptible to degradation due to environmental factors, namely pH, temperature, light, oxidation, and the presence of metal ions, which can cause degradation of the chromophore structure and color fading. Meanwhile, in anthocyanins, color is produced from the flavylium (cation) form which is stable in acidic conditions, but can undergo transformation into the chalcone form as the pH value increases, which causes color changes, as well as a decrease in pigment intensity during storage (Enaru et al., 2021), (Sigurdson et al., 2017) . In complex cosmetic systems such as emulsions, gels, or surfactant systems in hair care products, interactions with other formulation components can accelerate the oxidation or hydrolysis process of pigments. This instability is known to not only impact visual color changes, but also affect the quality and acceptance of the product by consumers. Therefore, the stability of pigments as colorants in cosmetic matrices is a crucial aspect that determines the quality, safety, shelf life of products, and the development of natural-based cosmetic formulations. Although various studies have evaluated the stability and biological activity of betalains and anthocyanins, most studies still focus on food or pharmaceutical applications, while comparative studies that specifically discuss the chemical stability of pigments from beetroot, dragon fruit, blackcurrant , mangosteen peel and black rice in the context of cosmetic formulations are still limited. In fact, the pH characteristics of the skin (±4.5–5.5) and scalp, as well as exposure to the external environment, require more specific stability evaluations for topical applications (Brooks et al., 2025).

Use of colorless corigen in skincare preparations has been widely applied in various forms of formulations such as creams, gels, lotions, and facial masks to enhance visual appeal while providing additional functional value. Natural pigments such as anthocyanins and betalains are often utilized in these formulations, for example in facial gels containing dragon fruit extract (Hylocereus polyrhizus) which provides a natural pink color, as well as antioxidant creams based on black rice (Oryza sativa L.) or blackcurrant (Ribes nigrum) which produces a distinctive purple color. In addition to functioning as natural dyes, these pigments also contribute as antioxidants that can protect the skin from oxidative stress.

Based on this background, this review aims to comprehensively examine the literature in the last 10 years regarding the pigment potential of Beta vulgaris , Ribes nigrum , Hylocereus polyrhizus, Garcinia mangostana and Oryza sativa L., as colorant co-products in skincare and haircare products. The main focus of the study includes chemical stability (the effect of pH, temperature, and light on oxidation and degradation of pigment structure), as well as its implications for the development of stable, effective, and safe natural-based cosmetic formulations.

METHODS

This study employed a literature review methodology. Articles were searched for on Google Scholar and PubMed using the keywords "natural dyes," "cosmetics," and "stability." A total of 50 articles relevant to the research topic and published within the last ten years were analyzed to identify trends and key findings.

RESULT AND DISCUSSION

Results

Beetroot (Beta vulgaris) as a source of Betalain pigments

Beetroot (Beta vulgaris L.) is a source of natural pigments that are widely used as colorant in cosmetic formulations, especially skincare. The main pigments contained in beetroot are betalains, which consist of betacyanins, such as betanin which gives red to purple colors, and betaxanthin which produces yellow to orange colors. Unlike anthocyanins which belong to the flavonoid group, betalains have a unique chemical structure and are water-soluble, thus providing their own characteristics in terms of stability and application in cosmetic systems (Kaba et al., 2024). From the physical stability aspect, betalain in beetroot is highly influenced by environmental factors such as temperature, light, and pH. Increasing temperature has been shown to accelerate the rate of pigment degradation, which is characterized by a significant decrease in color intensity, especially at temperatures above normal storage conditions. At temperatures around 25°C, color and bioactive content are relatively stable, while at higher temperatures (35–45°C) degradation accelerates, causing a decrease in color intensity and antioxidant activity (Kayın et al., 2019). In addition, exposure to light, especially ultraviolet light, also plays a role in accelerating pigment degradation, especially when combined with high temperatures, which can have a synergistic effect on the damage to the color structure (Sigurdson et al., 2017), (Hernández-Aguirre et al., 2021). The pH factor is also an important parameter in maintaining betalain stability, where this pigment tends to be more stable at acidic to neutral pH (around pH 4–7), whereas in extreme pH conditions, structural changes can occur which cause a decrease in color intensity (López-Solórzano et al., 2025).

In terms of chemical stability, betalains are known to be susceptible to oxidation reactions and degradation of their molecular structure, especially under suboptimal environmental conditions such as high temperatures, oxygen exposure, and extreme pH. The oxidation process can cause the breakdown of betalain into derivative compounds such as betalamic acid which have a paler color or even colorless, thereby reducing the aesthetic quality of the product (Kayın et al., 2019). In addition, this chemical degradation can also cause undesirable changes in color hue, which has the potential to affect the visual stability of cosmetic preparations.

In its application, betalain from beetroot not only functions as a natural dye, but also has biological activity that provides added value in skincare formulations. The high antioxidant content in betalain and other phenolic compounds plays a role in warding off free radicals caused by UV exposure, thereby helping to protect the skin structure, including preventing collagen degradation associated with the premature aging process. This is supported by research showing that the use of a cream containing 15% beetroot extract can inhibit the increase in MMP-1 expression and maintain collagen levels in skin exposed to UVB (Parwata et al., 2023) . Then, it can also be used for lip balm formulations with the use of beetroot extract in concentrations of around 3–10% is reported to be able to produce quite visible colors without disturbing the physical stability of the preparation. In addition, the betalain content in beetroot extract acts as an antioxidant that can help protect the lips from damage caused by free radicals (Hadi et al., 2023).

However, to maintain the color stability and biological activity of betalains in cosmetic formulations, an appropriate stabilization strategy is required. Beetroot is extracted using a more modern method using Deep Eutectic Solvents (DES) because it has been proven to increase the stability of betalains and is able to protect these compounds from oxidative and thermal degradation. Several approaches that can be used include adjusting the pH of the formulation to be slightly acidic around 4-7, the use of a buffer agent citrate (citric acid-sodium citrate), the addition of antioxidants, and encapsulation techniques that can protect the pigment from environmental influences (Smeriglio et al., 2016). (Hernández-Aguirre et al., 2021). By implementing this strategy, betalain from beetroot has great potential to be developed as a stable natural colorant that also provides functional benefits in skincare products.

Dragon Fruit (Hylocereus polyrhizus) as a source of Betalain pigments

Red dragon fruit (Hylocereus polyrhizus) is known to contain natural pigments in the form of betalains, especially betacyanins, which provide bright red to purple colors. These pigments are water-soluble and have potential as corrigens coloris in skincare formulations. The use of dragon fruit extracts, especially the skin, is increasingly being developed as a natural dye because it not only provides aesthetic value to products, but also has antioxidant activity that can help protect the skin from damage caused by free radicals (Sari et al., 2018). Thus, the use of dragon fruit in cosmetics not only functions as a dye, but also provides additional benefits for skin health. In skincare formulations, the addition of dragon fruit extract has been proven to improve the appearance of the color of the preparation so that it becomes more attractive and increases consumer acceptance. The natural red color produced from betalain can replace synthetic dyes that have the potential to cause irritation. In addition, the intensity of the resulting color can be adjusted to the concentration of the extract used in the formulation, thus providing flexibility in the development of cosmetic products such as gels with a usage concentration of 8% which provide moderate antibacterial and antioxidant effects [15] , lip creams at 2-4% usage concentrations for a stable hue without causing irritation (Putri et al., 2023), lip glosses at a concentration of 0.5% with unique colors (Santimangkalachai et al., 2018), peel-off facial masks at a concentration of 10% for antioxidant activity effects and good physical characteristics, as well as liquid soaps with a concentration of 0.9% which have moderate antioxidant activity (Ikram et al., 2020). This shows that dragon fruit has great potential as an alternative natural dye in the clean beauty -based cosmetics industry .

However, the use of betalain as a colorant has a major limitation, namely its relatively low stability against various environmental factors. The stability of this pigment is greatly influenced by pH, temperature, light, oxygen, and storage time. Betalain is known to be more stable at a pH of 4–5, while in conditions that are too acidic or alkaline, the pigment will experience degradation. In addition, exposure to high temperatures and light, especially ultraviolet light, can accelerate the damage of the pigment, which is characterized by a change in color to a paler or brownish color (Sari et al., 2018). The oxidation process also plays a role in reducing color intensity during storage, thus becoming a challenge in the formulation of stable cosmetic products (Setiawati & Sukmawati, 2018). To address these issues, various efforts have been made to improve the stability of betalains in skincare and cosmetic preparations. One commonly used approach is to adjust the pH of the formulation to the optimal range, which is around 4–5. In addition, microencapsulation techniques using materials such as maltodextrin or gum arabic have been shown to protect pigments from degradation due to environmental factors (Nurhadi et al., 2024) . Storage at low temperatures and the use of packaging that protects from light exposure are also important strategies in maintaining color stability. The addition of antioxidants to the formulation also helps inhibit the oxidation process, so that the color of the preparation can be maintained longer during the shelf life. From a chemical stability perspective, betalains in dragon fruit can experience degradation through oxidative reactions, hydrolysis, and breakdown of the molecular structure when exposed to outside optimal conditions, which can cause changes in color intensity and hue. Conditions such as high temperatures, extreme pH, and oxidation can accelerate the cleavage of betalain chromophore bonds, so cosmetic formulations must consider protective strategies such as the use of antioxidants or other stabilization techniques (Rodriguez et al., 2016).

The use of dragon fruit as a colorant has been applied in various forms of skincare preparations. Several studies have reported the use of dragon fruit peel extract in lip cream formulations with stable, homogeneous results and no irritation to users (Putri et al., 2023). In addition, dragon fruit extract is also used in the manufacture of liquid soap which shows attractive color results and good antioxidant activity (Ikram et al., 2020). This shows that dragon fruit has broad potential as a natural ingredient in the development of cosmetic products, especially as a safe and functional natural colorant. Recent research has explored dragon fruit extract in skincare gel formulations , showed that this extract was able to maintain physical stability, skin-compatible pH, and antioxidant and antibacterial activities after being formulated in a gel preparation, which supports its potential as an active ingredient in natural-based cosmetic products. The gel formulation also remained stable under various temperature conditions, strengthening the relevance of its application in topical skin care that requires a homogeneous texture and high bioactivity against free radicals, important factors in preventing skin aging and oxidative stress (Febrianti et al., 2025).

The most recommended extraction method is Ultrasound-Assisted Extraction (UAE) because it is able to increase the extract yield while minimizing the degradation of active betalain compounds through the use of relatively low temperatures and shorter extraction times (Chauhan et al., 2026) (Sari et al., 2026) . In addition, conventional methods such as maceration are still widely used, especially with aqueous ethanol solvent acidified using citric acid or acetic acid, because acidic conditions (around pH 4) have been proven to maintain pigment stability and prevent degradation during the extraction process (Dewi et al., 2020) . The use of ethanol is recommended over methanol because it is safer for cosmetic applications, but remains effective in extracting phenolic compounds and natural pigments [24] . Therefore, the UAE method or maceration with aqueous ethanol solvent under acidic conditions, low temperatures, and minimal light exposure is the most optimal and commonly used approach in extracting dragon fruit for cosmetic formulations.

Blackcurrant Fruit (Ribes nigrum) as source of anthocyanin pigments

Fruit (Ribes nigrum) is one of them source experience the richest anthocyanin , which provides spectrum color red old until purple concentrated . The dominant type of pigment found in fruit This is group anthocyanin glycosides , particularly delphinidin-3-rutinoside, delphinidin-3 glucoside, and cyanidin-3-O-glucoside. For get compound anthocyanin with optimal stability , method common extractions used is extraction solvent acidified aqueous extraction using ethanol or methanol with addition sour organic like sour citric or sour chloride . at pH ±2–3 for maintain form cation flavilium is the most stable . In addition to conventional methods such as maceration, modern techniques such as ultrasound-assisted extraction (UAE) are able to increase yield while minimizing thermal degradation through the use of lower temperatures and shorter extraction times (Wagner et al., 2023), (Azman et al., 2022). The color stability of blackcurrant anthocyanins depends strongly on the pH of the medium. At pH 3.0, anthocyanins are in the relatively stable flavylium cation form with high visual color intensity. Conversely, at pH 6.0, the compound changes to a neutral quinonoidal base form which is less stable and undergoes color degradation more rapidly (Azman et al., 2022). The anthocyanin degradation mechanism generally involves several reaction pathways, namely hydration, oxidation, and flavylium ring opening. At increased pH, the flavylium cation structure undergoes transformation into a colorless hemiketal (basic carbinol) form, then continues into a chalcone form which is unstable and easily degraded irreversibly (Modesto Junior et al., 2023).

In addition to pH, storage temperature and thermal treatment also affect anthocyanin stability. Studies on various blackcurrants reported that at 20 °C the anthocyanin concentration decreased gradually over time with a kinetic degradation model, while increasing temperature accelerated the degradation rate. Other studies have shown that storage at low temperatures such as 4 °C can extend pigment retention for months compared to storage at higher temperatures. In general, anthocyanins tend to be more stable at low temperatures (< 20 °C) and show faster degradation when increased above room temperature (Wagner et al., 2023) . The degradation mechanism is due to increasing the kinetic energy of the molecules, thus accelerating various chemical reactions that damage the pigment structure. Mechanistically, high temperatures accelerate the hydrolysis of glycosidic bonds, which separates the sugar group from the aglycone (anthocyanidin) so that the structure becomes more unstable. In addition, temperature also increases the rate of oxidation and thermal degradation, which causes the cleavage of the chromophore system in the flavylium ring (Modesto Junior et al., 2023).

Anthocyanin pigments, which are also the main pigments in Blackcurrant (Ribes nigrum) fruit, are known to be very sensitive to light exposure, especially ultraviolet (UV) radiation. A recent kinetic study reported that anthocyanins exposed to 25 W UV light experienced very rapid degradation with a rate constant (k) of 3.748 h^{-1} and a half-life ($t_{1/2}$) of only ±0.18 hours, while when exposed to 10 W fluorescent light, degradation was slower with k = 0.015 h^{-1} and $t_{1/2}$ of approximately 45.6 hours. These results indicate that light, especially UV, significantly accelerates the damage to anthocyanin structures and decreases color intensity, so that for the utilization of anthocyanin pigments such as those from blackcurrants, protection against light is required during storage and product application (Modesto Junior et al., 2023).

In its application as a colorant, blackcurrant anthocyanin extract is used in a range of concentrations that vary depending on the type of preparation. In natural hair dye formulations, anthocyanins are reported to be used in the range of 0.05–10% (w/w), with increasing concentrations producing higher color intensity, while the range of 0.5–5% is considered optimal to produce sufficiently intense colors with good washout resistance (Rose et al., 2018) . In contrast, in topical cosmetic preparations such as gels, creams, or emulsions, the concentrations used are generally lower, namely around 0.1–1%, with concentrations around 1% having been shown to be effective in hydrogel systems and capable of providing antioxidant activity without compromising the stability of the formulation (Petrov Ivanković et al., 2024).

In anthocyanin stabilization studies for natural dye formulations, light exposure negatively impacted color retention and accelerated the decline in antioxidant activity during storage. Therefore, for the application of anthocyanin pigments from blackcurrant in cosmetic products, it is necessary to consider light protection strategies, such as packaging that can block UV light, in addition to pH and temperature control during processing and storage (Tang et al., 2023) . The stability of anthocyanins from Ribes nigrum can also be improved through formulation strategies such as copigmentation and microencapsulation, which are able to protect the flavyllium cation structure from degradation due to oxygen, light, and temperature (Azman et al., 2022), (Tang et al., 2023).

Mangosteen (Garcinia mangostana L.) as a source of anthocyanin pigments

Mangosteen (Garcinia mangostana L.) is a fruit with many benefits, where the flesh and rind are often used in health and beauty products. Mangosteen has a reddish-black skin, with white flesh and has a sweet taste. This fruit is included in the Clusiaceae family. Mangosteen rind contains various active compounds including mangostin, flavonoids, tannins, and xanthones. The active compound in mangosteen rind is a natural pigment anthocyanin, which is a group of compounds from flavonoids (Tungadi et al., 2024). The anthocyanin compounds in mangosteen peel can produce distinctive colors ranging from red to blue. Anthocyanins are polar, meaning they dissolve easily in polar solvents such as water or ethanol. This polar nature allows the compounds to be easily extracted and applied to various water- or alcohol-based cosmetic products. The color intensity produced by the anthocyanin pigments in mangosteen peel depends on the concentration of the extract (Saidah & Nurdianti, 2024).

In mangosteen peel, high temperatures can cause the glycosidic bond to break, where the sugar compound in the anthocyanin core is released. This causes the flavylium ring to open and change into a chalcone compound or carbinol base. This change causes the color to become colorless or brown. Therefore, the maximum temperature used is 60°C-70°C because anthocyanins and bioactive compounds in mangosteen peel are thermolabile or cannot withstand high temperatures. In mangosteen peel, exposure to UV or light can trigger a photooxidation reaction, where the anthocyanin B ring structure is attacked by singlet oxygen. This causes the color to fade or experience permanent bleaching (Mukharomah et al., 2025) . Mangosteen peel extract is stable at a certain pH, the pH concentration of the extract can determine the color that will appear. At pH 1-3, which is very acidic and the most stable, it will produce a bright red color. At pH 4-5, it will produce a purple color that begins to fade slightly. At pH 6-7, the color will change to a brownish purple where the previous purple color will quickly fade and then turn brown. At pH 8 in an alkaline environment, the color will change to a blue-green color which is unstable (Asmorowati et al., 2024).

Mangosteen peel has the potential to be formulated as a colorant in various cosmetic preparations, one of which is as a colorant in lip balm products. In the lip balm preparation, mangosteen peel extract can produce a cream color with an extract concentration of 2.5%-10%. The addition of mangosteen extract to the lip balm preparation with a natural formulation including beeswax, almond oil, VCO, and honey will change the color of the preparation from initially white to cream with a distinctive aroma. The use of mangosteen peel extract in lip balm has been proven not to damage the quality of the lip balm preparation. The evaluation results show that the lip balm is safe to use on lips, namely between pH 4.5-7.0 (Rahayu et al., 2025). Cosmetics that can be applied as cosmetics other than lip balm are hair dyes. The dye that can be taken from anthocyanin compounds is a reddish color. Anthocyanin compounds are known to require additional substances so that the color can stick to the hair. A substance that successfully helps to bind to the hair is $FeSO_4$ with a concentration of 2% (w/v) in an acidic environment of pH 1-3. In an acidic environment, anthocyanins will change into a stable flavyllium cation form and iron ions help form a strong bond between the pigment and hair keratin. And by using mangosteen extract with a concentration of 10% (w/v), it can help provide a dark red color intensity (Prasetyo et al., 2026).

Black Rice (Oryza sativa L.) as a source of anthocyanin pigments

Black rice is a variety of rice (Oryza sativa L.) that is purple-black in color due to its high anthocyanin pigment content. Research shows that the anthocyanin content in ethanol extract of black rice can be up to five times higher than that of red rice. This is indicated by the anthocyanin pigment that dominates the pericarp, testa (seed coat), and aleurone layers in the vacuoles of its epidermal cells. The layers that make up the bran provide a higher efficiency of anthocyanin pigment extraction than extraction in the endosperm, which generally contains no or only a small amount of pigment. These dark pigments are dominated by the compounds cyanidin-3-glucoside (C3G) and peonidin-3-glucoside (P3G), which are chemically more resistant to degradation than the C3G compound due to the methylation process. on the phenolic B ring which reduces the chemical reactivity of the P3G compound structure (Yogaswara et al., 2024). Physically, the color spectrum produced by this pigment depends on the density of TAC (Total Anthocyanin Content) and proanthocyanidins. A high concentration of TAC will visually produce a black color, while a higher proanthocyanidin content will produce a red color (Mackon et al., 2021).

The chemical stability of anthocyanin compounds in black rice is strongly influenced by the equilibrium of the compound forms which depend on the level of acidity (pH). In very acidic conditions, with a pH range of 1.0 to 2.0, cyanidin-3-glucoside (C3G) is dominated by the flavylium cation form which gives a red color (Yogaswara et al., 2024). However, as the pH increases towards neutral conditions, such as at pH 4.5, a chemical transformation of C3G occurs which hydrates the flavylium cation into a colorless hemiketal (pseudobasic carbinol) structure. Continuing to increase the pH can accelerate degradation until finally the hemiketal can undergo irreversible degradation into a chalcone structure which is pale yellowish and more susceptible to oxidation than the flavylium cation (Jung et al., 2020) . This shows that the level of anthocyanin stability varies with changes in pH. Therefore, in formulating cosmetics, a pH regulating agent is needed to maintain the retention of the dark purple color of a preparation at a targeted pH of around 5.0 to effectively produce a distinctive purple color within a pH range that is safe for the skin (4.5 – 6.5) (Yogaswara et al., 2024). Several studies have shown that the addition of an acid solution can increase the effectiveness of maintaining the intensity of the natural purple color as well as the stability of the preparation during storage. In a study that formulated a peel-off gel mask containing 1% black rice ethanol extract, it was found that the purple color could be maintained at pH 5.0 with the addition of 1% HCl, as well as the use of a relatively low evaporation temperature (45°C) to minimize thermal degradation of the pigment (Yogaswara et al., 2024). A similar strategy was also applied to a topical gel preparation containing 0.1% extract with the addition of 10% citric acid which was able to maintain a pale pink color at a pH of around 5.5. The results of accelerated stability tests on the preparation for 3 months at 45°C showed no significant changes in pH (5.46 - 5.54), which remained within the ideal range for skin (4.0 - 6.0) and produced a stable pale pink color (Kucuk et al., 2026) . In addition, in lotion formulations containing black rice bran extract, the stabilization strategy involved the addition of antioxidants such as butylated hydroxytoluene (BHT) to prevent oxidation of components in the oil phase (Jufri et al., 2021) . This strategy suggests that the stability of natural pigments in cosmetics is influenced by a combination of chemical and formulation factors, including pH control, process temperature, and protection against oxidation.

In addition to pH, anthocyanin stability is also susceptible to temperature. Exposure to temperatures above 35°C during storage can trigger glycosidic bond hydrolysis and flavonoid ring opening, which converts anthocyanin pigments to polymeric brown (Jung et al., 2020) (Mackon et al., 2021) (Sari et al., 2026). Exposure to ultraviolet (UV) radiation triggers more rapid structural photodegradation at high pH, and excess moisture can also induce oxidation by free radicals (Rattanathanan et al., 2022) . In addition, the extraction method also affects the stability and quality of anthocyanins from black rice. Maceration using acidified ethanol (ethanol–HCl) or 96% ethanol is commonly used because it prevents the decomposition of thermolabile anthocyanins. In this process, ethanol as a semi-polar solvent is effective in extracting polar anthocyanins, while acidic conditions help maintain a stable flavylium form and improve color retention (Yogaswara et al., 2024). Extraction with 96% ethanol (1:4 w/v) for 24 hours at room temperature, as well as a concentration process using a rotary evaporator at low temperatures (±45–50°C) has been shown to minimize early thermal degradation of pigments (Kucuk et al., 2026). Conversely, longer extraction times and high evaporation temperatures (±80°C) can increase yield , but have the potential to accelerate the oxidative degradation of anthocyanins, which reduces their color quality (Jufri et al., 2021).

To overcome the risk of instability of anthocyanin molecules in black rice, several strategies can be applied to increase chemical stability, such as modifying the anthocyanin structure through acylation with caffeic acid. The acylation process has been shown to increase degradation resistance because it is able to protect the aglycone core from nucleophilic hydration of water, and increase the lipophilic properties of anthocyanins, thereby facilitating their interaction with cell membranes (Kong et al., 2023) . This shows that the acylation process has the potential to facilitate the integration of anthocyanins into fat-based cosmetics such as creams, while supporting the development of more stable anthocyanin products. The use of complexing agents with cycloamylose (CA) has been reported to increase the stability of anthocyanins from black rice extract (BRA). At pH 4, the BRA-CA complex showed a lower degradation rate (ka = 2.07×10^{-2} h^{-1}) compared to uncomplexed BRA (ka = 4.21×10^{-2} h^{-1}), and was slightly more stable compared to the use of 5% β -cyclodextrin (ka = 2.21×10^{-2} h^{-1}) after a thermal stability test at 95 °C for 24 hours. In addition, a photostability test using a UVA chamber for 24 hours showed that the BRA-CA complex experienced a decrease in degradation rate across the pH range (2–8), indicating increased light resistance. This increased stability is related to the ability of CA to form inclusion complexes with anthocyanins, thereby protecting the flavylium structure from degradation due to heat and photooxidation. Therefore, the CA addition strategy has the potential to be applied in natural pigment-based cosmetic formulations (Ma & Jing, 2020).

In its utilization, the physical characteristics of anthocyanins in black rice extract which are rich in antioxidants and concentrated pigments have shown stable results with a homogeneous purple color in various skincare preparations, such as peel-off gel masks that function to nourish and hydrate the face as well as in skin lightening lotion preparations (Yogaswara et al., 2024). With this, pH regulation and oxidative protection are crucial parameters in maximizing the potential of black rice as a stable and functional natural dye in cosmetic preparations (Rattanathanan et al., 2022).

Discussion

Degradation of the Chemical Structure of Betalain and Anthocyanin

Betalains and anthocyanins are natural pigments widely used as colorant co-products in the food and pharmaceutical industries due to their ability to provide attractive colors and antioxidant activity. Chemically, these two compounds have fundamental differences that affect their stability. Betalains are nitrogen-containing pigments and are divided into betacyanins (red-purple) and betaxanthins (yellow-orange), while anthocyanins belong to the flavonoid group with a basic structure of flavylium cations (Li et al., 2019). These differences cause different degradation mechanisms and responses to environmental factors.

Betalain degradation is generally influenced by temperature, pH, oxygen, and light. At high temperatures, the betalain structure is damaged, causing a decrease in color intensity. Chemically, this degradation occurs through the hydrolysis of the aldimine bond (N=C) which produces betalamic acid and cyclo-DOPA-glycoside. In addition, extreme pH conditions and the presence of oxygen also accelerate the pigment oxidation process (Fatjria et al., 2023) . However, betalain is relatively stable at pH 3–7 with optimum stability at pH around 5–6. On the other hand, anthocyanin has a stability that is highly dependent on environmental pH. Under acidic conditions, anthocyanin is in the form of a stable flavylium cation and is red, but at neutral to alkaline pH it will undergo a structural change to a colorless or bluish form. The anthocyanin degradation process includes the hydrolysis of the glycosidic bond that produces anthocyanidins, ring opening, and oxidation and polymerization reactions. External factors such as high temperature, light, and oxygen also accelerate this degradation (Enaru et al., 2021).

A comparison of the two pigments shows that betalains have superior stability over a wider pH range than anthocyanins, but are more sensitive to high temperatures. Conversely, anthocyanins are very stable under acidic conditions but readily degrade at neutral to alkaline pH. This is an important consideration in their use as colorant coagulants, especially in product formulations that have varying environmental conditions. In application, pigment degradation can cause color changes, decreased product quality, and reduced biological activity. Therefore, strategies are needed to increase stability, such as controlling pH, temperature, light exposure, and the addition of stabilizing agents such as antioxidants or chelating agents. By understanding the characteristics and degradation mechanisms of betalains and anthocyanins, their use as colorant coagulants can be optimized according to the desired formulation conditions.

Stability Analysis of Betalain and Anthocyanin as Colorant Corigens in Cosmetics

Based on Table 1, it can be seen that each natural pigment source has different physical and chemical stability characteristics, thus affecting its effectiveness as a colorant in skincare formulations. From the aspect of temperature stability, anthocyanin pigments in blackcurrants show relatively good stability at low temperatures, but experience rapid degradation at high temperatures. Meanwhile, betalains from beetroot and dragon fruit tend to be sensitive to high temperatures, although they are still quite stable at room temperature (Wagner et al., 2023) , (Kayın et al., 2019). Anthocyanin pigments in mangosteen peel are thermolabile because they begin to experience damage at temperatures of 60–70°C, while anthocyanins in black rice studies experience hydrolysis at temperatures above 35°C which causes a color change to brown (Jung et al., 2020) . This shows that in general all natural pigments have limitations at high temperatures, so temperature control is needed in formulation and storage.

In terms of pH stability, anthocyanins found in blackcurrants, mangosteen peel, and black rice show the best stability under acidic conditions (pH 1–3), where the resulting color is more intense and stable. However, at neutral

Table 1: Comparison of Characteristics of Natural Corigen from Various Sources

Parameter	Beetroot	Dragon fruit	Blackcurrant	Mangosteen skin	Black Rice
Parts & Pigments	Tubers: Betacyanin and Betaxanthin	Skin: Betalain Meat: Betalain	Fruit: Anthocyanin (Delphinidin, C3G)	Fruit skin: Anthocyanin	Rice bran: Anthocyanins (C3G, P3G)
Temperature Stability	High temperature sensitive (more than 35–45°C), stable at room temperature (25°C)	Skin: Room & high temperature degradation (1st order) Meat: High temperature sensitive, stable in gel	Low temperature stable, high temperature rapid degradation	Thermolabile, damaged at 60-70 ° C	Hydrolysis ≥ 35 ° C (color change from purple to polymeric brown)
pH stability	Stable pH 4-7, extreme pH reduces color intensity to a paler color.	Skin: Stable pH ~5, extreme pH rapidly degrades Meat: Stable acidic pH	Stable pH 3, rapid degradation pH 6	Stable pH 1-3 red, pH 4-5 purple, pH >6 unstable	pH 4.5 transparent purple, pH 5.5 pale pink, the higher the pH the color degrades (pales)
Light Stability	Sensitive to UV, causing increased degradation leading to damage to the color structure.	Skin: Very light sensitive, more stable with encapsulation Meat: Light sensitive, needs protection	Very UV sensitive (t1/2 0.18 hours), normal light is more stable	UV sensitive, permanent bleaching	UV sensitive, fast photodegradation rate
Oxidation and Degradation	Vulnerable to oxidation, betanin becomes betalamic acid	Skin: Oxidation chromophore cleavage Meat: Oxidation, reduces antioxidant activity	Degradation by light/high pH	High temperature breaks the glycosides à chalcone	Rapid oxidation, thermal & UV degradation
Cosmetic Potential	Decorative colorant and antioxidant for anti-aging cream with a usage percentage of 15% and lip balm with a percentage of 3-10%.	Red-purple dye, for lip gloss preparations 0.5%, Lip cream 2-4%, Skincare gel 8%, peel-off facial mask 10%, and liquid soap 0.9%	Semi-permanent hair dye, antioxidant	Lip balm dye, Hair dye	Peel-off gel mask (1%; purple), Topical gel (0.1%; pale pink), Brightening lotion (10%; light purple)
Superiority	Natural coloring, high antioxidant, anti-aging	Skin: Strong colors Meat: Stable in gel & bioactive	Intense color, good retention, low pH	Strong color & easy to extract	Concentrated pigment, high antioxidant (anthocyanin 123.2mg/100g)
Weakness	Unstable light & temperature	Skin: Rapidly degrades without encapsulation Meat: Very light sensitive	Very sensitive to UV & high pH	Unstable at high temperatures & alkaline pH	Unstable pH > 4.5, UV sensitive
Chemical Stability Strategy	pH adjustment (4-7); using *buffer* (citric *acid – sodium citrate*); Encapsulation	Microencapsulation using maltodextrin/gum Arabic. pH adjustment by adding acetic acid/citric acid *buffer. Ultrasound Assisted Extraction (UAE)* extraction method.	Acid pH setting (±2-3), using acidified solvents during extraction, micro-encapsulation and co-pigmentation, hermetic packaging.	Addition of Sodium Metabisulfite (antioxidant protects compounds in the preparation from Oxidation reactions), Addition of 2% FeSO4 (stabilizes anthocyanins)	Addition of acid solution: 1% HCl, (stable at evaporation temperature of 45°C), 10% citric acid, and antioxidant (BHT)
Reference	(Kayın et al., 2019) (Hernández-Aguirre et al., 2021) (Parwata et al., 2023)	(Febrianti et al., 2025) (Putri et al., 2023) (Santimangkalachai et al., 2018) (Ikram et al., 2020) (Setiawati & Sukmawati, 2018) (Chauhan et al., 2026)	(Wagner et al., 2023) (Azman et al., 2022), (Modesto Junior et al., 2023) (Tang et al., 2023)	(Mukharomah et al., 2025) (Petrov Ivanković et al., 2024)	(Yogaswara et al., 2024) (Kucuk et al., 2026) (Jufri et al., 2021) (Kong et al., 2023) (Ma & Jing, 2020)

to alkaline pH, these pigments experience rapid degradation and significant color changes (Azman et al., 2022) . In contrast, betalains from beetroot and dragon fruit have a wider stability range, namely at pH 4–7, making them more compatible with the pH of human skin which ranges from 4.5–5.5 (López-Solórzano et al., 2025) . This advantage makes beetroot and dragon fruit more compatible for application in skincare products and decorative cosmetics without requiring extreme pH adjustments. In terms of light stability, almost all natural pigments show high sensitivity to ultraviolet light exposure . Anthocyanins in blackcurrants even experience very rapid photodegradation with a short half-life, while mangosteen peel can experience permanent bleaching due to light exposure. Black rice also shows rapid photodegradation, while betalains from beetroot and dragon fruit remain sensitive to light although their stability can be improved through encapsulation techniques (Hernández-Aguirre et al., 2021) . Therefore, light is a major challenge in utilizing natural pigments as colorant co-products.

In addition, in terms of chemical stability, all natural pigments are susceptible to oxidation and degradation of their molecular structure. Betalains in beetroot can undergo oxidation to betalamic acid , which causes a decrease in color intensity, while anthocyanins in mangosteen peel and black rice can experience degradation due to the influence of temperature, pH, and light, causing changes in structure to become colorless or brownish (Jung et al., 2020). However, various strategies such as encapsulation, the addition of antioxidants, and the use of nanocarriers have been shown to increase the stability of pigments both physically and chemically (Kong et al., 2023), (Nurhadi et al., 2024). Based on the comparison in the table, dragon fruit and beetroot can be categorized as the most optimal natural co-origens used in cosmetics because they have a balance between stability and ease of formulation. Although betalains from both plants can still experience degradation, the stability of betalain pigments can be increased through a pH adjustment formulation approach (4-7) using a buffer (citric acid-sodium citrate) (Hernández-Aguirre et al., 2021), microencapsulation techniques using maltodextrin/gum arabic (Nurhadi et al., 2024) , and the use of the Ultrasound Assisted Extraction (UAE) extraction method (Chauhan et al., 2026). In addition, in the skin pH range (around 4-7), the resulting color tends to be more stable than anthocyanins from other sources that easily change color due to pH fluctuations.

In terms of application, dragon fruit extract has been widely used in various cosmetic products such as lip balm. creams , peel-off masks , and gels because they provide attractive colors and have antioxidant activity (Febrianti et al., 2025), (Putri et al., 2023), (Setiawati & Sukmawati, 2018) . This advantage makes it not only function as a colorant (corrigen coloris), but also provide additional benefits such as protection against free radicals and anti-aging effects. Compared with other sources that are more susceptible to degradation or discoloration, dragon fruit is more flexible and practical to formulate, making it one of the best choices in the development of natural ingredient-based cosmetics.

CONCLUSION

Based on study literature in ten year last , fifth sources of pigments are beetroot, red dragon fruit , blackcurrant, skin mangosteen and rice black show potential big as corigen colorist in formulation skincare and cosmetics Decorative . Betalains in beetroot and dragon fruit, as well as anthocyanins in blackcurrants, mangosteen, and black rice, provide a rich color spectrum and possess biological activities such as antioxidant, photoprotective, and anti-aging properties that are beneficial for skin health. However, the main challenge lies in physical and chemical stability. All pigments have been shown to be sensitive to UV light, high temperatures, alkaline pH, and oxidation, although the degree of instability varies between pigment types. Anthocyanins are more stable at acidic pH, while betalains are relatively more stable at acid-neutral pH. Cosmetic formulations containing these pigments must consider environmental factors and interactions with formulation components, as inappropriate conditions can cause color fading, discoloration, or decreased bioactivity. Strategies such as pH adjustment, low-temperature storage, antioxidant addition, encapsulation, and the use of nanocarriers effectively increase pigment stability. With the right strategies, these two natural pigments from five plants have great potential as safe, environmentally friendly, and stable natural dyes with potential added functional value in various skincare and decorative cosmetic products.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest related to the preparation, authorship, and publication of this review article.

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