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Anthocyanins: Natural Pigments with Multifaceted Health Benefits for Humans

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Abstract

Anthocyanins are water-soluble flavonoid pigments found in fruits, vegetables, flowers, and grains, known for their red, purple, and blue colors. They belong to the phenolic class and are typically found in glycosylated forms, providing UV protection and defense against biotic and abiotic stress. Anthocyanins have health-promoting properties due to their strong antioxidant capacity, anti-inflammatory, antimicrobial, anti-cancer, cardioprotective, and neuroprotective effects. Primary dietary sources include berries, grapes, red cabbage, eggplant, black rice, and purple sweet potatoes. However, their stability is often limited by environmental conditions like light, temperature, and pH, making them challenging for food and nutraceutical applications. Anthocyanins are structurally diverse due to variations in their aglycone backbone, glycosylation patterns, and acylation with organic acids. Glycosylation enhances anthocyanin water solubility and stabilizes the flavylium cation, while acylation increases pigment stability against light and pH fluctuations. Extracted anthocyanins offer numerous health benefits and eco-friendly applications, but challenges like low stability and limited bioavailability need to be addressed through advanced processing, formulation, and biotechnological approaches.

Keywords*:* Anthocyanins, Natural food colorants, Antioxidant activity, Chronic disease prevention and Phenolic compounds

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Introduction

Anthocyanins are a group of water-soluble flavonoid pigments responsible for the red, purple, and blue colors in many fruits, vegetables, flowers, and grains. These naturally occurring pigments, which are part of the phenolic class and usually exist in glycosylated forms, help plants look their best, protect them from harmful UV rays, and ward off both biological and environmental stresses. Known as the flavylium (2-phenylchromenylium) ion, anthocyanins have a positive charge at the oxygen atom on the C-ring of their basic structure; they are a form of flavonoid (Khoo *et al*., 2017). The primary dietary sources of anthocyanins include berries, grapes, red cabbage, eggplant, black rice, and purple sweet potatoes (Tsuda, 2012). Beyond their role as natural food colorants, anthocyanins have attracted significant attention for their potential health-promoting properties in humans. Numerous studies have demonstrated their strong antioxidant capacity, as well as anti-inflammatory, antimicrobial, anti-cancer, cardioprotective, and neuroprotective effects (Wallace, 2011; He & Giusti, 2010). These biological activities are largely attributed to their ability to scavenge reactive oxygen species (ROS), modulate enzyme activity, and regulate signaling pathways involved in inflammation and cellular stress (Pojer *et al*., 2013). The degree of hydroxylation and methylation of the anthocyanidin skeleton, pH, co-pigmentation, and metal ion complexation are some of the elements that impact the variance in anthocyanin colour (Khoo *et al*., 2017; Andersen & Jordheim, 2006).

In plants, anthocyanins perform essential ecological functions, including attracting pollinators and seed dispersers, protecting against ultraviolet (UV) radiation, and serving as defense compounds against pathogens and herbivores (Gould, 2004). They also play a role in mitigating oxidative stress during environmental challenges such as drought, temperature extremes, and nutrient deficiency.

In terms of human health, anthocyanins have recently attracted a lot of attention because of the many beneficial effects they have on inflammation, cancer, obesity, and heart health (Wallace & Giusti, 2015; He & Giusti, 2010). These bioactive substances are plentiful in plants that are pigmented, such as berries, grapes, red cabbage, purple maize, and others. They play a significant role in the diet. One problem with using them in food and nutraceuticals is that their stability is typically compromised by factors including light, temperature, and pH (Khoo *et al*., 2017).

The growing recognition of anthocyanins as natural colorants and health-promoting agents has driven research into their biosynthesis, genetic regulation, metabolic engineering, and biotechnological production using plant tissue culture systems (Jaakola, 2013).

Types of Anthocyanin in Plants

Anthocyanins, the glycosylated forms of anthocyanidins, are structurally diverse due to variations in their aglycone backbone, glycosylation patterns, and acylation with organic acids. These structural modifications influence their color expression, stability, solubility, and bioactivity, thereby determining their functional roles in plants and their potential applications in food, pharmaceutical, and nutraceutical industries (Andersen & Jordheim, 2006; Khoo *et al*., 2017).

1. Classification Based on Aglycone Structure (Anthocyanidins)

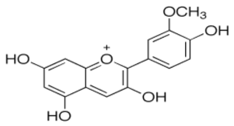
The core anthocyanidin structure, the flavylium cation, can be hydroxylated or methylated at specific positions, leading to six major naturally occurring anthocyanidins: cyanidin, delphinidin, pelargonidin, peonidin, petunidin, and malvidin. These differ in their substitution pattern on the B-ring, which directly affects their hue from the orange-red tones of pelargonidin to the bluish-purple shades of delphinidin and malvidin. Cyanidin is the most widely distributed in nature, while malvidin, common in grapes and wine, exhibits greater stability due to its higher degree of methylation (He & Giusti, 2010; Wallace & Giusti, 2015).

2. Classification Based on Glycosylation

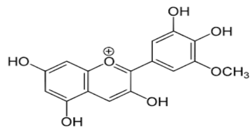
In plants, anthocyanidins are rarely found in the aglycone form; they typically occur as glycosides, with sugars such as glucose, galactose, rhamnose, arabinose, or xylose attached primarily at the C3 position of the C-ring, and sometimes at C5 or C7. Glycosylation enhances anthocyanin water solubility, stabilizes the flavylium cation, and affects absorption and bioavailability in humans. Examples include cyanidin-3-O-glucoside in black rice and delphinidin-3-O-rutinoside in grapes (Khoo *et al*., 2017).

3. Classification Based on Acylation

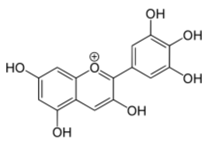
Many anthocyanins undergo acylation, where the sugar moieties are esterified with aromatic acids (e.g., p-coumaric, ferulic, caffeic) or aliphatic acids (e.g., malonic, acetic). Acylation contributes to increased pigment stability, particularly against light and pH fluctuations, and often results in shifts in color intensity due to intramolecular co-pigmentation effects (Yousuf *et al*., 2016). Acylated anthocyanins are abundant in red cabbage, purple sweet potato, and certain ornamental flowers. Peonidin, petunidin, delphinidin, pelargonidin, malvidin, and cyanidin are the six most common types of anthocyanidins found in plants (Shown in Figure 1).



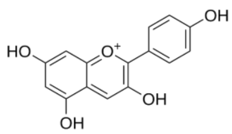
Peonidin



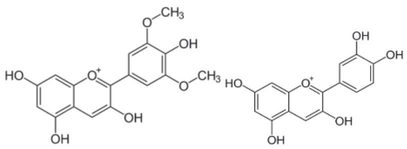
Petunidin



Delphinidin



Pelargonidin



Cyanidin Malvidin

(Fig:-1. Major Anthocyanidins in Plants)

Peonidin is one example of the many methylated anthocyanidins found in plants. According to Bakowska (2005), this chemical displays a vivid magenta hue. Peonidin is mostly found in red wines, berries, and grapes. There is malvidin, a purple-colored O-methylated anthocyanidin that is commonly found in blue flowers, especially the Summer Wave Blue type (Tanaka *et al*., 1998). Also, according to Mazza and Francis (1995), the primary red pigment in red wine is malvidin. Exuding a deeper shade of dusty crimson with age (Barnard *et al*., 2011). Methylated anthocyanidins are also found in petunidin. It dissolves in water and appears as a dark crimson or purple pigment (Bakowska, 2005). According to Slimestad and Solheim (2002), petunidin is present in blackcurrants. according to Yabuva *et al*., (1997), even in certain flowers' purple petals.

Health Benefits and Eco-Friendly Uses of Anthocyanins

The majority of patients with urinary tract infections (UTIs) need to be treated in the comfort of their own homes. Annually, nearly one million people in the US visit hospitals due to chronic and recurrent UTIs. The majority of these illnesses are caused by Escherichia coli. Drinking cranberry juice or eating cranberries whole has a long history of usage in warding against urinary tract infections. According to Kang *et al*., (2013), cyanidin-3-O-glucoside, a component found in cranberries, may reduce the likelihood of acquiring a UTI by preventing bacteria from adhering to the bladder walls. Cranberry juice, pills, tablets, and concentrates are just a few of the various cranberry products on the market. How well each one works to prevent UTIs varies. Despite blueberries' reputation for anthocyanins, the efficacy of cyanidin-3-O-glucoside and cyanidin-3-O-rutinoside in the prevention or treatment of urinary tract infections (UTIs) remains unknown (Koh *et al*.,2015& Liu *et al*., 2014). There has been limited research on the effects of these chemicals on the uropathogenic E. coli and Pseudomonas aeruginosa strains that are commonly detected in UTI patients' urine. Heart disease, diabetes, IBD, UTIs, dysentery, periodontitis, mouth ulcers, and oral infections are among the ailments that they aid in managing. The neuroprotective properties of anthocyanins further bolster brain wellness. These natural substances are amazing for preventing and treating diseases because of their antioxidant, anti-inflammatory, antibacterial, and anticancer characteristics (figure 2).

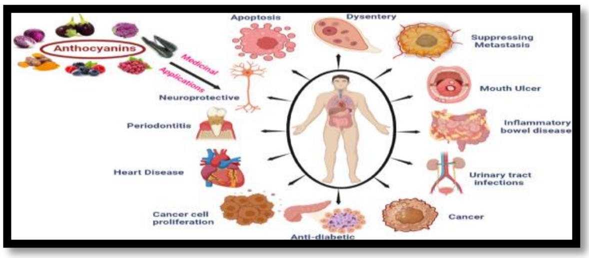


Fig: 2. a graphical depiction illustrating the diverse medical applications of ACNs (Source from www.biorender.com).

Extracted Anthocyanins from Fruits, Flowers, and Vegetables, Along With Their Medicinal, Food, And Cosmetic Uses Given Here-

1. **Blueberries – Applications of Extracted Anthocyanins**

Medicinal Uses- Help fight cancer, anti-obesity, anti-inflammation, prevent degenerative diseases, prevent heart disease, support liver health, improve brain function, protect heart, manage diabetes, enhance vision.

Food Supplementary- Available as dried fruit, wine, jam, pulp powder, vinegar, fruit juice, colorant, and flavoring additives (Ma *et al*.,2018).

Cosmetic Uses- Sun protection factor, UV-A protection factor (Duan *et al*.,2022) (Schiavon *et al*.,2019).

2. Strawberry – Applications of Extracted Anthocyanins

Medicinal Uses-Oxidative stress relief, prevention of inflammation, protective against different types of cancer, and heart illness (Giampieri *et al*., 2013).

Food Supplementary-Natural colorant in yogurts, milkshakes, ice cream, and pies.

Cosmetic Uses-Protects human dermal fibroblasts against UV-A induced damage (Sandulachi & Tatarov2012), (Gasparrini *et al*.,2017).

3.Sweet Cherry – Applications of Extracted Anthocyanins

Medicinal Uses-Weight reduction is supported, cancer is reduced, inflammation is reduced, muscle damage is minimised, oxidative stress is guarded against, and neuroprotective benefits are exerted (Habib *et al*., 2017; McCune *et al*., 2011).

Food Supplementary-Used in brined, canned, frozen, jammed, dried or juiced forms; fruit-based refreshment (Willig, 2022).

4.Plum – Applications of Extracted Anthocyanins

Medicinal Uses-Antioxidant, relieves fever, anti-hyperlipidemic, anti-osteoporosis, anti-cancer, anti-diabetic, prunes for acidity, headaches, fever, and degenerative changes (Mishra & Vyas 2021), (Gong *et al*., 2021).

Food SupplementarySauce, juice, pickled plums, liquor, condiment, or beverages.

Cosmetic Uses-Skin care and anti-aging product (Stierlin *et al*., 2018).

5. Hibiscus – Applications of Extracted Anthocyanins

Medicinal Uses- Antioxidant, anti-fertility, anti-fungal, wound healing, enhance immune response, anti-diabetic, neuroprotective, cardio-protective, liver protection, anti-pyretic (Missoum, 2018).

Food Supplementary Used in jam, jelly, juice, syrup, wine, pudding, cakes, gelatin, ice-cream, tarts, sauces, spices, pies, brewed tea, and dried forms (Islam,2019).

Cosmetic Uses-Promotes hair growth, skin whitening, anti-aging (Sim & Nyam, 2011).

6. Apple- Application of Extracted Anthocyanins

Medicinal Uses- Protecting the gastrointestinal tract from drug-induced harm, aiding in weight loss and bone health, fighting cancer and diabetes, alleviating asthma and pulmonary issues, preventing cardiovascular disease, and acting as an antioxidant are all benefits of this compound.

Food Supplementarybread, jams, dried goods, sweet bakery items (cakes, scones, muffins, etc.), juice, wine, confectionery, and brittle bakery items (cookies, crackers, etc.).

Cosmetic Uses -Benefits include a decrease in inflammation of the skin, an antioxidant, anti-aging properties, and regulation of sebum production. The study conducted by Lyu *et al*., in 2020

7.Black Carrot - Application of Extracted Anthocyanins

Medicinal Uses Anti-cancer, anti-microbiological, wound-healing, anti-cancer, renal-hepatic, ocular-, diabetes-, and cardiovascular-related disorders.

Food Supplementary- Carrot pomace in baking goods, pickles, cakes, jam, ice cream, sauces, high-fiber biscuits, and functional beverages.

Cosmetic Uses -Skin hydration, skin elasticity, anti-inflammatory, anti-acne, and antioxidant properties (Rahman and Atta-ur 2005).

8.Black beans- - Application of Extracted Anthocyanins

Medicinal Uses -Anti-oxidant, diabetic, inflammatory, mutagenic, obesity, and cancer, hypercholesterolemia, and reducing the risk of coronary heart diseases.

Food Supplementary Asian black turtle bean dishes include curries, burritos, smokey baked beans, black turtle bean patties, and black turtle bean soup with pork ribs.

Cosmetic Uses-Substances used as ingredients in hair growth, anti-aging, and cosmetic treatments (Meenu *et al*., 2023) (Lai *et al*.,2012)

9. Red rice- Application of Extracted Anthocyanins

Medicinal Uses-Lower blood pressure, inflammation, diabetes, allergies, and cardiovascular disease.

Food Supplementary Adirasam, kozhukattai, modakam, payasam, semiya, uppuma, flaked rice, puffed rice, adai, appam, idli, dosai, idiyappam, and pongal are some of the names for this type of rice.

Cosmetic Uses-hair growth-promoting, Anti-aging (Rathna *et al*.,2019)

10. Purple sweet potato- Application of Extracted Anthocyanins

Medicinal Uses -Helps with diabetes, fights bacteria, reduces inflammation, protects the liver and kidneys, fights cancer, protects the nervous system, reduces obesity, and promotes good gut health.

Food Supplementary Fermented milk, yoghurt, vinegar, juice, alcoholic beverages, pasta, noodles, porridge, fortified cereal, flour, snack bar, soup, bread (made from orange-fleshed sweet potato flour), cookies, crackers and yoghurt.

Cosmetic Uses- anti-inflammation, Skin whitening (Alam,2021) (Choi *et al*.,2011)

11. Purple corn- Application of Extracted Anthocyanins

Medicinal Uses-Benefits include lowering blood pressure, promoting heart health, preventing obesity and cancer, increasing antioxidant defences, reducing inflammation, and inhibiting carcinogenic genes.

Food Supplementary Corn starch used as a natural dye in acidic drinks, corn flour used to make doughs and tortillas and masa for chips

Cosmetic Uses- Anti-aging agent, anti-acne actions and anti-inflammatory (Lao *et al*.,2017) (Colombo *et al*.,2021) (Cai *et al*.,2023)

12. Red cabbage- Application of Extracted Anthocyanins

Medicinal Uses gout, anti-obesity, hypocholesterolemic, nephroprotective, neuroprotective, anti-diabetic, anti-oxidant, hepatoprotective, cardioprotective, and a cure for gastric ulcers and migraines.

Food Supplementary Items such as gummi candies, food items dyed with natural ingredients, and bio-based films for storing cheese in the fridge

Cosmetic Uses- Use as a face cream to promote collagen production, skin tissue strength, less pigmentation loss, and enhanced development and health. (Ghareaghajlou *et al*., 2021) (Abedi *et al*., 2022) (Trilokchandran *et al*., 2019)

Conclusion

Anthocyanins are a wide-ranging family of flavonoid pigments found in plants. They help plants deal with stress, change their colour, and alter their interactions with their environment. Their stability, solubility, and colour expression are dictated by the structural variety that results from differences in hydroxylation, methylation, glycosylation, and acylation. Anthocyanins have received a lot of interest for their potential medical and health-promoting uses, in addition to their roles in plants.

Research has demonstrated that anthocyanins can help neutralise free radicals and lower oxidative stress due to their powerful antioxidant and anti-inflammatory properties. They protect the heart by lowering blood pressure, enhancing vascular health, and blocking lipid oxidation. Improving glucose metabolism and insulin sensitivity is associated with their anti-diabetic potential, and their neuroprotective effects may aid in reducing cognitive decline and improving memory. Through their ability to modulate cell signalling pathways, suppress tumour development, and induce apoptosis in cancer cells, anthocyanins also demonstrate anticancer potential. In addition to preventing oxidative damage to retinal cells and enhancing visual acuity, they help keep the eyes healthy.

The creation of functional foods, nutraceuticals, and medicines might be greatly enhanced by the use of anthocyanins, which act as both natural colourants and medicinal agents. Nevertheless, advancements in processing, formulation, and biotechnology are necessary to overcome obstacles including poor bioavailability and poor stability. To ensure that anthocyanins are included into health promotion and disease prevention programs to their full potential, further study is needed in these areas. Fruits ranging in colour from red to blue, such as berries and blackcurrants, contain antioxidant-rich anthocyanin pigments. Black carrots, crimson cabbage, and purple potatoes are examples of foods rich in anthocyanins, which may have a protective effect against disease.

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