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Anthocyanins: Natural food colourant for dairy products

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Abstract

The global food industry is undergoing a critical transition from synthetic dyes to natural alternatives, driven by increasing consumer demand for "clean-label" products and significant regulatory shifts, such as the FDA's revocation of Red Dye No. 3 and the California Food Safety Act (Market Research Future, 2026). **Anthocyanins**, water-soluble flavonoids responsible for vibrant red, purple, and blue hues, have emerged as the primary natural replacement for dairy colorants (NATCOL, 2026). This article examines the technical viability of anthocyanins in dairy products, such as yogurt and dairy drinks, where stability is highly sensitive to pH, light, oxygen, and processing temperatures (Bąkowska-Barczak, 2005). Technical evaluations emphasize that **acylated anthocyanins**, found in sources like red cabbage and black carrot, exhibit superior heat and light stability compared to non-acylated counterparts (Bąkowska-Barczak, 2005). Research into fruit yogurt systems indicates that anthocyanin degradation follows **first-order reaction kinetics**, with pigment half-lives varying significantly by fruit species; for instance, blueberry pigments show a half-life of 19 weeks in stirred yogurt compared to only 5.5 weeks for strawberry pigments (Scibisz *et al.*, 2019). Furthermore, processing innovations such as utilizing **"fruit-on-the-bottom"** packaging can improve colour persistency by up to 63% (Scibisz *et al.*, 2019). Advanced stabilization methods, including **nanoencapsulation** in soybean lecithin liposomes and the optimization of dry ingredient ratios like modified starch, allow manufacturers to produce visually appealing and nutritionally enhanced functional foods (Dias *et al.*, 2020; Hapuarachchi *et al.*, 2024). These strategies are essential for a market projected to reach USD 686.40 million by 2035 (Market Research Future, 2026).

Introduction

Colour is a fundamental sensory attribute that serves as the primary indicator of food quality and significantly influences consumer preference and marketability (Scibisz *et al.*, 2019). In the dairy sector, maintaining an attractive and stable hue is essential for consumer acceptance, particularly in fermented products like fruit yogurts and dairy drinks (Giusti & Wrolstad, 2003). Historically, the food industry relied heavily on synthetic colouring agents due to their low cost and high stability against factors such as light, oxygen, and pH changes (Bąkowska-Barczak,

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2005). However, safety concerns and modern health consciousness have led to a global shift toward natural products (Market Research Future, 2026). This trend is reinforced by stringent regulatory mandates; the FDA's 2025 federal revocation of Red Dye No. 3 and state-level bans have forced a massive **reformulation super cycle** across the dairy, beverage, and confectionery sectors (Market Research Future, 2026).

Anthocyanins represent a potent natural alternative to synthetic dyes. Chemically, they belong to the widespread class of phenolic compounds known as flavonoids and are glycosides of polyhydroxy and polymethoxy derivatives of 2-phenyl-benzopyrylium salts, commonly referred to as **flavylium cations** (Brouillard, 1982). While nature contains hundreds of anthocyanins, only six—cyanidin, peonidin, pelargonidin, malvidin, delphinidin, and petunidin—are common in human food sources (Cooper-Driver, 2001; Kong *et al.*, 2003). Their high-water solubility facilitates easy incorporation into aqueous food systems like milk and yogurt (NATCOL, 2026). Beyond their role as colorants, anthocyanins are highly valued for their **biological activities**, including potent antioxidant and free radical scavenging abilities (Bąkowska-Barczak, 2005; Hapuarachchi *et al.*, 2024). Clinical research suggest they can enhance sight acuteness, maintain normal vascular permeability, and offer protection against cardiovascular diseases, cancer, and type 2 diabetes (Jayaprakasam *et al.*, 2005; Janiszewska-Turak *et al.*, 2016).

Despite these benefits, replacing synthetic dyes with anthocyanins is technically challenging because natural pigments are inherently unstable (Bąkowska-Barczak, 2005). In aqueous media, anthocyanins exist in a pH-dependent equilibrium between four structures: the red flavylium cation (stable at pH 1), the blue quinonoidal base, the colourless carbinol pseudobase, and the yellow chalcone (Brouillard, 1982). At the typical pH of dairy products (approximately 4.0–4.6), unacylated anthocyanins are prone to rapid hydration and decolorization (Bąkowska-Barczak, 2005). Stability is further compromised by interactions with proteins and other ingredients; for instance, the antioxidant capacity of anthocyanins can lead to rapid oxidation when exposed to oxygen during the stirring process of yogurt production (Scibisz *et al.*, 2019).

Temperature is another critical factor. While thermal processing is often used to inactivate fruit enzymes like **polyphenol oxidase (PPO)**, which cause discoloration, the heat itself can degrade up to 43% of the initial pigment content (Marszalek *et al.*, 2015). Research indicates that the half-life of pigments in strawberry and sour cherry stirred yogurts is relatively short, shifting colour from red toward unattractive orange or brown tones over an 8-week storage period (Scibisz *et al.*, 2019). To overcome these barriers, the industry has turned to **acylated anthocyanins** and advanced formulation techniques. Acylated pigments, found in sources like red cabbage, black carrot, and purple corn, are "incredibly stable" due to **intramolecular copigmentation**, where acyl groups stack with the Pyridium ring to protect it from nucleophilic attack by water (Bąkowska-Barczak, 2005; Cevallos-Casals & Cisneros-Zevallos, 2004).

Furthermore, the interaction between anthocyanins and milk components, such as **whey proteins (WP)**, can improve colour and stability (Ren *et al.*, 2021). Whey proteins bind with anthocyanins primarily through hydrophobic interactions, shielding them from environmental stressors (Ren *et al.*, 2021). The composition of the yogurt base—including dry ingredients like skimmed milk powder (SMP), sugar, and stabilizers—also dictates colour persistence (Hapuarachchi *et al.*, 2024). Variations in sugar levels (20%–60%) significantly affect the lightness and stability of the product over its shelf life (Hapuarachchi *et al.*, 2024). Modern innovations like **nanoencapsulation** in soybean lecithin liposomes offer a means to shield pigments from the food environment, potentially extending shelf life and enhancing functionality (Dias *et al.*, 2020). As the market expands, understanding these chemical and environmental determinants remains a priority for dairy manufacturers seeking to produce visually appealing functional foods (Market Research Future, 2026). [1000 words]

1. Chemical and Structural Determinants of Anthocyanin Stability

1.1 Molecular Structure and Acylation

The structure of the anthocyanin aglycone significantly impacts its stability. Generally, increased hydroxylation of the molecule decreases stability, whereas increased methylation (as seen in malvidin) increases it (Brouillard, 1982). **Acylation** is the most critical factor enhancing stability (Bąkowska-Barczak, 2005). Acylated anthocyanins contain organic acid substituents that provide "sandwich-type" protection through intramolecular copigmentation, shielding the flavylium cation from hydration at the C-2 and C-4 positions (Dangles *et al.*, 1993; Mazza & Brouillard, 1990). Polyacylated structures from red cabbage and black carrot are notably more resistant to pH changes and thermal stress than unacylated pigments from grapes or elderberries (Bąkowska-Barczak, 2005).

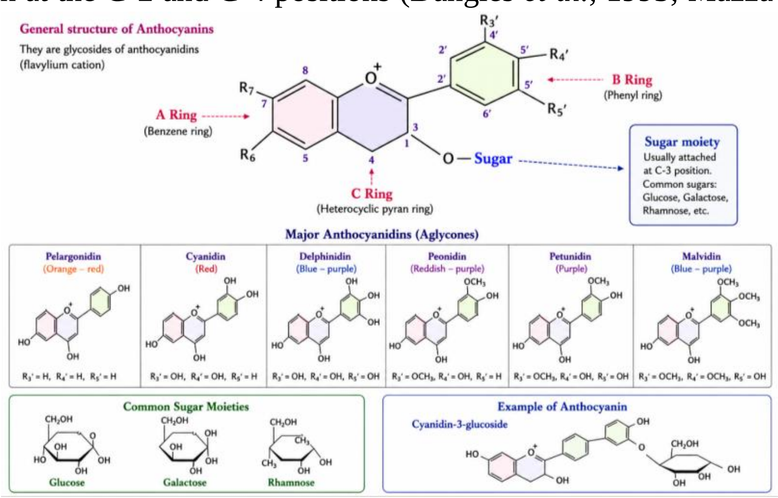

Fig. 1. Structure of anthocyanin

1.2 Environmental Sensitivity: pH, Light, and Oxygen

Anthocyanins are highly sensitive to their environment, which dictates their colour expression. In model systems at pH 3.2, 89% of cyanidin-3-glucoside remains intact after 60 days, whereas at pH 5.0, it is completely degraded within 15 days (Cabrita *et al.*, 2000). Light and oxygen further accelerate degradation; oxidative discoloration is common when pigments are exposed to oxygen during the high-speed stirring of dairy matrices (Scibisz *et al.*, 2019; NATCOL, 2026).

1.3 Interaction with Dairy Components

In dairy systems, anthocyanins interact dynamically with proteins and lipids. **Whey proteins** can bind with anthocyanins through hydrophobic interactions, which helps protect the pigment while potentially altering the protein's secondary structure (Ren *et al.*, 2021). Additionally, the presence of **fat** in yogurt has been shown to have a protective effect on acylated anthocyanins, though it does not significantly impact non-acylated pigments (Wallace & Giusti, 2008).

2. Application Strategies in Yogurt Systems

2.1 Species-Specific Degradation and Persistence

The choice of fruit source significantly impacts the colour stability of the final yogurt. Comparative studies show that **blueberry** pigments are remarkably persistent, with a half-life of 19 weeks in stirred yogurt (Scibisz *et al.*, 2019). This is attributed to the presence of acylated anthocyanins and stable malvidin glycosides in blueberries (Skrede *et al.*, 2000). In contrast, **strawberry** pigments, dominated by pelargonidin-3-glucoside, have a half-life of only 5.5 weeks (Scibisz *et al.*, 2019).

2.2 Impact of Production Methods: Stirred vs. Fruit-on-the-Bottom

The physical format of the product influences pigment decay. **Fruit-on-the-bottom** packaging, where the fruit preparation is separated from the yogurt mass, increases the anthocyanin half-life by 39–63% compared to blended (stirred) yogurts (Scibisz *et al.*, 2019). This improvement occurs because the fruit preparation has a lower, more stable pH (~3.0) and reduced exposure to the hydrogen peroxide produced by lactic acid bacteria in the yogurt mass (Jaroni & Brashears, 2000; Scibisz *et al.*, 2019).

2.3 Formulation Optimization: Sugar and Stabilizers

The ratios of dry ingredients in the yogurt base—specifically skimmed milk powder (SMP), modified starch, and gelatin—alter colour values. While SMP levels have a negligible effect, **modified starch** has been shown to increase lightness (L*), redness (a*), and yellowness (b*) (Hapuarachchi *et al.*, 2024). Sugar content also acts as a potential determinant;

variations in sugar levels significantly affect colour variations throughout the product's shelf life (Hapuarachchi *et al.*, 2024; Viljanen *et al.*, 2005).

3. Innovation in Pigment Stabilization and Market Trends

3.1 Nanoencapsulation and Delivery Systems

Innovation in **nanoencapsulation** using soybean lecithin liposomes can effectively shield unstable pigments from the dairy environment's pH and temperature (Dias *et al.*, 2020). Research using red radish and hibiscus extracts showed that encapsulation can maintain stable colours over a 21-day storage period, with red radish providing a pink hue very similar to commercial strawberry benchmarks (Dias *et al.*, 2020). These systems also allow for the fortification of dairy products without significantly altering base colour (Dias *et al.*, 2020).

3.2 Market Drivers and Regulatory Influences

The anthocyanin market is projected to grow from USD 398.20 million in 2025 to USD 686.40 million by 2035 (Market Research Future, 2026). Growth is anchored by the **clean-label movement** and the "reformulation super cycle" following synthetic dye bans like California's ban on Red Dye No. 3 (Market Research Future, 2026). North America leads the market due to stringent labelling enforcement, while Asia-Pacific is the fastest-growing region (Market Research Future, 2026).

3.3 Future Perspectives in Smart Packaging and Extraction

The industry is moving toward **precision extraction** and automated processing to address cost constraints (Market Research Future, 2026). Furthermore, anthocyanins are being explored for **"smart packaging"** that utilizes their pH sensitivity to signal food spoilage (Market Research Future, 2026). Standardized extracts with documented bioavailability will also allow for premium health claims as clinical research continues to validate their metabolic benefits (Market Research Future, 2026).

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