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Innovative Insights into Blue Pigment Extraction from Floral Crops: A Comprehensive Review

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Abstract

Because of their biocompatibility, ecological advantages, and extensive uses in many sectors, such as the food, cosmetics, pharmaceutical, and textile industries, natural floral pigments have attracted a lot of interest recently. The intricate biological processes required to synthesise blue dyes give them a unique significance among these pigments since they are so rare in nature. Here we take a look at what's new in the field of floral crop blue pigment extraction, characterisation, and applications. It delves into the chemical make-up of blue pigments such anthocyanins and new ways of extracting them, as well as the molecular processes that control their colouration. The article also discusses the difficulties of keeping pigments stable and provides some ideas on how to improve extraction efficiency and find new uses for them in industry. Improving extraction techniques and increasing the economic viability of natural blue pigments are crucial in meeting the increasing demand for environmentally friendly and all-natural colourants.

Keywords: Blue pigments, anthocyanins, flavonoids, natural dyes, flower coloration, extraction techniques, ultrasound-assisted extraction

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1. Introduction

1.1 Background and Significance

For ages, people have turned to plant pigments for their dyes and colourants needs in clothing, cooking, personal care, and even medicine. Synthetic dyes are often detrimental to both humans and the environment; hence, there has been a renaissance in interest in natural pigments as a substitute (Masyita et al., 2025). Because of their aesthetic value and relative rarity in nature, blue pigments in particular are quite desirable. The majority of flowers' blue shades are caused by intricate anthocyanin-based chemicals. These compounds are affected by factors such as pH, interactions with metal ions, and the effects of co-pigmentation (Bahreini et al., 2024).

Blue pigments are visually appealing and economically valuable, but they are notoriously difficult to extract because of their chemical instability and susceptibility to environmental variables. The yield and colour retention of traditional extraction procedures are often low. Nevertheless, new extraction methods such as enzyme-assisted extraction (EAE), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) have shown potential in enhancing pigment stability and yield (Kalyani & Muhammed, 2025).

1.2 Objectives of the Study

The primary objectives of this review are:

- To explore the molecular and biochemical mechanisms governing blue pigmentation in flowers.
- To evaluate the efficiency and effectiveness of various extraction techniques for blue pigments.
- To identify the challenges associated with blue pigment extraction and propose potential solutions.
- To assess the commercial applications of natural blue pigments and their industrial significance.
- To provide insights into future research directions and technological improvements in natural dye extraction.

2. Pigment Composition in Flowers

The colouration of flowers is primarily attributed to the presence of natural pigments, which serve functional roles beyond aesthetics, such as attracting pollinators and protecting plants from environmental stressors (Narbona et al., 2021). The blue colouration in flowers is particularly rare and results from complex biochemical interactions involving anthocyanins, flavonoids, and metal ion complexation.

2.1 Types of Flower Pigments

The primary classes of pigments responsible for flower colouration include:

2.1.1 Anthocyanins

Flowers often have red, purple, or blue colours due to anthocyanins, the most prevalent pigments in plants. These chemicals are flavonoids that are soluble in water and are produced via the phenylpropanoid pathway. Metal ion interactions, co-pigmentation with flavonoids, and the pH of the vacuoles in which anthocyanins are kept are the factors that impact the colour that these pigments display (Bahreini et al., 2024).

- The primary anthocyanins involved in blue pigmentation are delphinidin, malvidin, and petunidin.
- Co-pigmentation with flavonoids and metal ions like aluminium and magnesium enhances the intensity of blue colour.

2.1.2 Flavonoids

Flowers' yellow, red, and blue hues are attributed, in part, to flavonoids, a vast class of polyphenolic chemicals. In interactions between plants and insects, they serve as signalling molecules and UV protectors (Cheng et al., 2024).

- Flavonols and flavones provide a base for colour modification through pH changes and metal ion binding.
- They enhance anthocyanin stability through complexation and co-pigmentation.

2.1.3 Betalains

Betalains are nitrogen-containing pigments found primarily in plants of the order Caryophyllales. They are less common in blue flowers but can contribute to purple and red hues.

2.1.4 Carotenoids

Colours like yellow, orange, and red in flowers are mostly caused by carotenoids, which are pigments that are soluble in lipids. Although they do not contribute to the blue hue on their own, they provide a multi-colored look when combined with flavonoids and anthocyanins.

2.2 Molecular Mechanisms Governing Blue Coloration

The formation of blue colour in flowers involves multiple biochemical and structural factors:

- **pH Dependence:** Higher pH levels in vacuoles tend to produce blue shades, while lower pH leads to red or purple hues (Cheng et al., 2024).
- **Metal Ion Binding:** Complexation of anthocyanins with metal ions like Al^{3+} and Mg^{2+} stabilizes the blue form of anthocyanins.
- **Co-Pigmentation:** Flavonoids and other phenolic compounds enhance the blue colour by forming complexes with anthocyanins and stabilising their structure.
- **Vacuolar Environment:** The vacuole's internal environment, including the concentration of organic acids and metal ions, influences pigment stability and colour expression.

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3. Extraction Techniques for Natural Dyes

Efficient extraction of blue pigments from flowers requires optimising the yield and stability of anthocyanins and flavonoids. Traditional methods often suffer from low efficiency and pigment degradation. However, modern techniques have enhanced extraction rates and preserved pigment stability.

3.1 Conventional Methods

Traditional extraction methods include solvent extraction and maceration, which rely on aqueous or organic solvents to dissolve and extract pigments from plant tissues.

- **Water and Ethanol-Based Extraction:** Aqueous and ethanol-based solvents are widely used for anthocyanin extraction due to their high solubility in polar solvents. However, this method often results in pigment degradation due to exposure to light and heat.
- **Acidified Solvent Extraction:** Acidification of solvents (e.g., with hydrochloric or citric acid) enhances anthocyanin stability during extraction.
- **Maceration:** Soaking plant materials in a solvent for a long time at room temperature is the key to this technique. It takes a lot of time but is easy.

3.2 Innovative Extraction Techniques

Recent advancements have introduced more efficient and environmentally friendly extraction techniques:

3.2.1 Ultrasound-Assisted Extraction (UAE)

In order to improve solvent penetration and pigment release, UAE use ultrasonic waves to break down plant cell walls.

- High extraction efficiency within a shorter time frame.
- Reduces thermal degradation of pigments.

(Kalyani & Muhammed, 2025)

3.2.2 Microwave-Assisted Extraction (MAE)

MAE involves using microwave radiation to heat plant material, increasing the diffusion rate of pigments into solvents.

- Rapid extraction process with high pigment yield.
- Enhanced preservation of pigment stability.

(Bahreini et al., 2024)

3.2.3 Enzyme-Assisted Extraction (EAE)

Enzymes like cellulase and pectinase are used by EAE to liberate pigments from inside cells by breaking down cell walls.

- Improved extraction efficiency and reduced solvent use.
- Environmentally friendly and sustainable.

(Masyita et al., 2025)

3.2.4 Supercritical Fluid Extraction (SFE)

SFE uses supercritical CO_2 as a solvent to extract pigments under high pressure and temperature.

- High selectivity and minimal solvent residue.
- Maintains pigment purity and stability.

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4. Characterization of Blue Pigments

Understanding the chemical and physical properties of blue pigments is crucial for improving extraction and application.

4.1 Chemical Properties

- **Anthocyanins:** Delphinidin, petunidin, and malvidin exhibit characteristic absorption peaks between 520–580 nm.
- **Stability:** Blue pigments are highly sensitive to pH, light, and oxygen exposure.
- **Metal Ion Binding:** Complexation with Al^{3+} and Mg^{2+} enhances stability.

4.2 Environmental and Structural Factors

- **pH Influence:** Blue pigments are more stable at neutral to slightly alkaline pH.
- **Temperature Sensitivity:** Higher temperatures accelerate pigment degradation.
- **UV and Light Sensitivity:** Exposure to light can lead to pigment oxidation and colour loss.

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5. Applications of Natural Blue Pigments

5.1 Textile Industry

- Natural blue dyes are used in eco-friendly fabric dyeing.
- Improved colourfastness through metal ion complexation.

5.2 Food and Pharmaceutical Industry

- Used in beverages, confectionery, and nutraceuticals as natural colourants.
- Anthocyanins have antioxidant, anti-inflammatory, and antimicrobial properties.

(Masyita et al., 2025)

5.3 Cosmetic Industry

- Blue pigments are used in lipsticks, eyeshadows, and skincare products.
- Improved stability through encapsulation and pH adjustment.

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6. Challenges and Future Prospects

6.1 Technical Challenges

- Low pigment stability under industrial processing conditions.
- Need for scalable and cost-effective extraction methods.

6.2 Environmental and Economic Considerations

- High production costs associated with natural pigment extraction.
- Need for eco-friendly and sustainable production processes.

6.3 Future Research Directions

- Development of genetically modified plants with enhanced blue pigment production.
- Exploration of novel co-pigmentation and stabilisation techniques.
- Expansion of industrial applications and commercial viability.

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7. Conclusion

Potentially far superior than synthetic dyes in terms of sustainability and environmental friendliness are natural blue pigments derived from flowers. A more thorough comprehension of pigment composition, extraction efficiency, and stabilisation procedures is required for the complicated blue colouration that is based on anthocyanins. There are still issues with scalability and cost reduction, however innovative approaches like UAE, MAE, and EAE have shown increased yields and stability. Research into molecular processes and extraction technology has to be ongoing if blue pigments are to expand their commercial uses in textiles, food, and cosmetics.

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