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Bioactive Plant Pigments as Natural Colorants: Chemistry, Extraction, and Therapeutic Potential

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Abstract: The increasing awareness of the environmental and health concerns associated with synthetic dyes has stimulated renewed interest in plant-derived natural colourants. Bioactive plant pigments such as anthocyanins, carotenoids, and quinines not only impart attractive colours but also exhibit a wide range of pharmacological activities. This review comprehensively examines bioactive plant pigments used as natural colourants, with particular emphasis on their chemical nature, extraction strategies, and therapeutic potential. Major pigment sources including *Hibiscus sabdariffa*, *Euterpe oleracea* (açaí berry), *Juglans regia* (walnut), and *Crocus sativus* (saffron) are discussed in terms of taxonomy, pigment composition, phytochemistry, traditional uses, antimicrobial properties, and industrial relevance. Conventional and advanced extraction techniques such as solvent extraction, ultrasound-assisted extraction, microwave-assisted extraction, and cold press extraction are critically reviewed for their efficiency and sustainability. The therapeutic activities of selected pigments, including antifungal, antibacterial, antitussive, antihypertensive, and antidiabetic effects, are highlighted. The review concludes that plant-based pigments represent promising eco-friendly alternatives to synthetic dyes, offering added health benefits and broad applicability in food, pharmaceutical, cosmetic, and textile industries.

Keywords: Bioactive plant pigments; Natural colourants; Anthocyanins; Carotenoids; Quinones; Hibiscus sabdariffa; Euterpe oleracea; Juglans regia; Crocus sativus; Green extraction technologies; Therapeutic potential; Sustainable dyes.

INTRODUCTION

Color has played a crucial role in human civilization, influencing food acceptance, textile aesthetics, cultural practices, and medicinal formulations. Historically, natural pigments derived from plants, animals, and minerals were the sole sources of color before the advent of synthetic dyes in the late nineteenth century. However, growing concerns regarding the toxicity, environmental persistence, and carcinogenic potential of synthetic colorants have renewed scientific interest in plant-based natural pigments (1–3).

Plant pigments are not merely coloring agents; they are often biologically active secondary metabolites synthesized for plant defence, pollinator attraction, and stress adaptation. Many of these compounds demonstrate antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and anticancer activities, making them attractive as multifunctional ingredients in food, pharmaceutical, cosmetic, and textile industries (4–6). This dual role as colorants and therapeutic agents positions plant pigments uniquely at the intersection of sustainability and health innovation.

Recent advances in green extraction technologies, analytical chemistry, and molecular pharmacology have significantly improved pigment recovery, stability, and bioavailability, overcoming many limitations previously associated with natural dyes, such as low yield, poor fastness, and instability (7, 8). Consequently, plant pigments are increasingly recognized as viable alternatives to synthetic colorants in industrial applications.

Table 1: Types of plants using Alternatives to synthetic dyes

S.no	Plant Source	Pigment Type	Colour
1.	**Hibiscus** (Hibiscus Rosa-Sinensis)	Anthocyanin's	Red-Purple
2.	**Acai Berry** (Euterpe Oleracea)	Anthocyanin's	Purple
3.	**Walnut** (Juglans)	Jug lone	Brown-Black
4.	**Saffron** (Crocus Statius)	Crocin	Yellow-Orange

NATURAL COLOURANTS

Natural colourants are coloring substances obtained from biological sources, including plants, microorganisms, insects, and minerals. Among these, plant-derived colorants dominate due to their availability, cultural acceptance, and broad spectrum of colors. Natural colourants can be classified based on chemical structure, solubility, and chromophore type (9). Unlike synthetic dyes, natural colourants often contain complex mixtures of pigments and co-pigments, such as flavonoids, tannins, organic acids, and sugars, which influence shade, stability, and binding affinity to substrates. These interactions are especially relevant in textile dyeing and food coloration, where pH, temperature, light exposure, and metal ions can significantly alter color expression (10–12).

From a toxicological perspective, most plant-derived pigments are considered **Generally Recognized as Safe (GRAS)** at dietary levels, although standardized toxicity and dose-response studies are essential for pharmaceutical use (13). Regulatory agencies worldwide increasingly favour natural colorants, further driving industrial adoption response studies are essential for pharmaceutical use (13). Regulatory agencies worldwide increasingly favour natural colorants, further driving industrial adoption.

PLANT PIGMENTS: CHEMISTRY AND FUNCTIONAL PROPERTIES

Plant pigments arise primarily from **secondary metabolic pathways**, including the phenylpropanoid, terpenoid, and shikimate pathways. The major classes include **anthocyanins, carotenoids, betalains, and quinines**, each possessing distinct chemical and functional characteristics (14, 15).

Anthocyanin's

Anthocyanins are **water-soluble flavonoid glycosides** responsible for red, purple, and blue hues in flowers, fruits, and leaves. Structurally, they are based on the **flavylium cation**, and their color is highly pH-dependent, shifting from red in acidic conditions to blue in alkaline environments (16). This pH sensitivity, while valuable for natural indicators, poses stability challenges in industrial formulations (17).

Anthocyanin's exhibit potent **free radical scavenging activity**, metal chelation, and enzyme modulation, contributing to cardiovascular, neuroprotective, and antidiabetic effects (18).

Carotenoids

Carotenoids are **lipophilic tetraterpenoids** responsible for yellow to orange coloration. Unlike anthocyanin's, carotenoids are more stable to pH but susceptible to oxidation and photo-degradation (19). Certain carotenoids, such as crocin in saffron, are uniquely water-soluble due to glycosylation, broadening their application spectrum (20).

Quinones and Related Pigments

Quinones, including naphthoquinones such as jug lone, are darker pigments often associated with **antimicrobial and allopathic properties**. Their strong binding affinity to proteins and cellulose makes them effective natural dyes, particularly for textiles and wood staining (21).

1. HIBISCUS

Fig 1: Hibiscus Rosa-Sinensis

Table 2: Taxonomy of Hibiscus rosa sinensis

TAXONOMICAL CLASSIFICATION	
Kingdom	Plantae
Subkingdom	Tracheobionta-Vascular plants
Super division	Spermatophyta-Seed plants
Division	Magnoliophyta-Flowering plants
Class	Magnoliopsida-Dicotyledons
Subclass	Dilleniidae
Order	Malvales
Genus	Hibiscus L.-Rosemallow
Family	Malvaceae
Species	Hibiscus rosa sinensis L.-Shoeblack plant

IMPORTANCE OF EXTRACTION AND STANDARDIZATION

Efficient extraction is critical for maximizing pigment yield, preserving bioactivity, and ensuring batch-to-batch consistency. Traditional extraction techniques, such as maceration and Soxhlet extraction, are simple but often solvent-intensive and time-consuming (22). Modern approaches, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), and pressurized liquid extraction, offer improved efficiency, reduced solvent usage, and better preservation of heat-sensitive compounds (23–25).Standardization of extracts using chromatographic and spectroscopic techniques is essential to correlate **chemical composition with biological activity**, particularly for therapeutic applications (26).

Taxonomy

Hibiscus sabdariffa L., commonly known as roselle, belongs to the family **Malvaceae**, which includes economically and medicinally important genera such as *Gossypium* and *Abelmoschus*. The plant is an annual or perennial shrub widely cultivated in tropical and subtropical regions, particularly in Africa, India, Southeast Asia, and parts of Central America. Taxonomically, *H. sabdariffa* is divided into two main varieties: *H. sabdariffa* var. *sabdariffa*, primarily cultivated for its fleshy red calyces, and var. *altissima*, grown mainly for fiber production (27).

The plant exhibits erect growth with deeply lobed leaves and distinctive bright red calyces that surround the seed capsule. These calyces are the principal source of pigments and bioactive compounds and are harvested at maturity when pigment concentration is maximal (28).

Phytochemistry of Hibiscus

The phytochemical profile of *H. sabdariffa* is dominated by anthocyanins, which are responsible for the characteristic deep red coloration of the calyces. The major anthocyanins identified include delphinidin-3-O-sambubioside and cyanidin-3-O-sambubioside, along with smaller quantities of their glucoside derivatives. These pigments coexist with flavones such as quercetin and kaempferol, organic acids (citric, malic, tartaric), and phenolic acids like protocatechuic acid (29).

Anthocyanins in hibiscus are glycosylated and often acrylate, which influences their color stability and antioxidant activity. The presence of organic acids not only contributes to the sour taste but also stabilizes anthocyanins by maintaining an acidic environment favourable for the flavylium cation form (30).

Antifungal Activity

Hibiscus extracts have demonstrated significant antifungal activity against a range of pathogenic fungi, including *Candida albicans*, *Aspergillus niger*, and *Trichophyton* species. Studies indicate that aqueous and ethanoic extracts of hibiscus calyces inhibit fungal growth by disrupting cell membrane integrity and interfering with ergo sterol synthesis, a key component of fungal cell membranes (31).

Anthocyanin's and phenolic acids act synergistically to exert fungi static and fungicidal effects, with inhibition zones comparable to standard antifungal agents at higher concentrations. Additionally, hibiscus extracts have shown the ability to inhibit fungal biofilm formation, which is a critical factor in antifungal resistance (32).

Traditional and Ethno medicinal Uses

Traditionally, *H. sabdariffa* has been extensively used in African, Ayurveda, and Middle Eastern systems of medicine. The dried calyces are commonly prepared as herbal teas and beverages for their **cooling, diuretic, and digestive properties**. In folk medicine, hibiscus is used to manage hypertension, liver disorders, fever, and urinary tract infections (33).

In Indian traditional practices, hibiscus preparations are also used externally for wound healing and hair growth, while in African communities, the plant is valued for its antimicrobial and anti-inflammatory effects. The long history of dietary consumption supports its safety profile and cultural acceptance (34).

Anthocyanin Extraction Methods

Conventional Extraction

Conventional extraction of anthocyanin's from hibiscus calyces typically involves **solvent maceration or Soxhlet extraction** using polar solvents such as water, ethanol, or methanol acidified with organic or mineral acids. Acidification (commonly 0.1% HCl or citric acid) enhances anthocyanin stability and extraction efficiency by maintaining acidic conditions (35).

However, prolonged extraction times and high solvent consumption are major limitations of conventional techniques. Thermal degradation and oxidation can also reduce pigment quality if extraction conditions are not carefully controlled (36).

Advanced Extraction Techniques

Modern extraction technologies have been developed to overcome these limitations. **Ultrasound-assisted extraction (UAE)** improves anthocyanin yield by inducing cavitation, which disrupts plant cell walls and enhances mass transfer. UAE significantly reduces extraction time and solvent usage while preserving bioactivity (37).

Microwave-assisted extraction (MAE) offers rapid heating and efficient extraction but requires careful optimization to avoid anthocyanin degradation. **Pressurized liquid extraction** and **subcritical water extraction** are emerging green technologies that allow selective extraction by tuning temperature and pressure, making them promising for industrial-scale production (38).

Textile Staining Procedure Using Hibiscus Pigments

Natural dyeing of textiles using hibiscus anthocyanins involves multiple steps to ensure adequate color uptake and fastness. Cotton, silk, and wool are the most suitable fibres due to their ability to form hydrogen bonds with anthocyanin molecules. Prior to dyeing, fabrics are scoured to remove impurities and improve dye penetration (39).

Mordanting is a critical step in natural dyeing. Alum (potassium aluminium sulphate) is commonly used as a mordant to enhance color brightness and fixation, while iron salts produce darker, more muted shades. The dyed fabric is immersed in an aqueous hibiscus extract maintained at pH 4–5 and heated gently between 60–80°C for 30–60 minutes with continuous agitation (40).

Post-dyeing treatments, including tannin application and mild cross-linking agents, can significantly improve wash and light fastness. Although natural dyes generally exhibit lower fastness than synthetic dyes, optimized mordanting and fixation strategies have demonstrated promising results for sustainable textile applications (41).

Significance of Hibiscus Pigments as Natural Colourants

Hibiscus anthocyanin's represent a valuable class of natural colorants due to their **intense coloration, water solubility, and associated health benefits**. Their application extends beyond food and beverages to cosmetics, pharmaceuticals, and eco-friendly textiles. The combination of colorant functionality with antimicrobial and antioxidant properties offers a competitive advantage over synthetic dyes (42).

Challenges remain in terms of stability and large-scale standardization; however, advances in encapsulation and formulation science are rapidly addressing these issues. Consequently, hibiscus pigments continue to attract attention as sustainable, multifunctional natural colorants (43).

Açaí Berry (*Euterpe oleracea*)

Botanical Background and Source of Pigments

Açaí berry is obtained from *Euterpe oleracea*, a palm species native to the Amazon rainforest, particularly in Brazil, Colombia, and Venezuela. The fruit is a small, dark purple drupe traditionally consumed as pulp-based beverages and pastes. In recent decades, açaí has gained global attention as a **functional food and natural pigment source**, largely due to its intense coloration and high antioxidant capacity (44).

The deep purple to black color of açaí pulp is primarily attributed to a high concentration of anthocyanins, which are localized mainly in the fruit's epicarp and mesocarp (45).

Fig 2: ACAI BERRY (Euterpe oleracea Mart)

Pigments in Açaí Berry

The dominant pigments in açaí are **anthocyanins**, particularly **cyanidin-3-O-glucoside** and **cyanidin-3-O-rutinoside**, which together account for the majority of the total anthocyanin content. Minor pigments include peonidin derivatives and polymeric anthocyanin complexes formed during processing and storage (46).

The anthocyanin profile of açaí is influenced by factors such as ripeness, geographic origin, and post-harvest handling. Compared to other berries, açaí exhibits relatively high pigment density, making it an efficient natural colorant for food and beverage applications (47).

Phytochemistry

Beyond anthocyanins, açaí berries contain a complex mixture of **polyphenols, flavonoids, proanthocyanidins, phenolic acids, tocopherols, and phytosterols**. The lipid fraction of açaí pulp is notable for its high content of oleic acid, contributing to both nutritional value and oxidative stability (48).

Phenolic acids such as frolic, vanillin, and syringe acids enhance antioxidant activity and may act synergistically with anthocyanins. This complex phytochemical composition supports the classification of açaí as a multifunctional bioactive matrix rather than a single-compound source (49).

Table 3: Taxonomy and common name of Acai Berry (Euterpe oleracea Mart)

TAXONOMICAL CLASSIFICATION	
Kingdom	Plantae
Subkingdom	Trichophytes
Binomial name	Euterpe Oleracea
Division	Magnoliophyta
Class	Liliopsida
Subclass	Euterpe oleracea
Order	Arecales
Genus	Euterpe
Family	Arecaceae (Palm tree)
Species	Euterpe oleracea

Antibacterial and Antifungal Activity

Açaí extracts have demonstrated **broad-spectrum antimicrobial activity**, particularly against Gram-positive bacteria such as *Staphylococcus aureus* and *Streptococcus* species. The antibacterial effect is attributed to anthocyanins and phenolic acids that disrupt bacterial cell membranes and interfere with enzyme systems involved in energy metabolism (50).

Antifungal studies have shown inhibitory effects against *Candida albicans* and filamentous fungi, with evidence suggesting membrane destabilization and oxidative stress induction as primary mechanisms. These findings support the potential use of açaí pigments as **natural antimicrobial colorants** in food preservation and topical formulations (51).

Traditional and Ethno medicinal Uses

In indigenous Amazonian communities, açaí has long been consumed as a **staple energy source** and used medicinally to treat fever, digestive disorders, skin infections, and fatigue. The pulp is often fermented or consumed fresh, while seed and leaf extracts are used in traditional remedies (52).

Traditional knowledge emphasizes the restorative and anti-inflammatory effects of açaí, which aligns with modern findings related to oxidative stress reduction and immune modulation. The integration of traditional use with scientific validation has significantly increased global acceptance of açaí-based products (53).

Extraction Procedures for Açaí Pigments

Conventional Extraction

Anthocyanins from açaí pulp are commonly extracted using **acidified aqueous ethanol or methanol**, with solvent polarity optimized to maximize pigment solubility. Mechanical decupling is followed by solvent maceration, filtration, and concentration under reduced pressure to minimize thermal degradation (54).

Although effective, conventional extraction methods are limited by solvent consumption and pigment instability during prolonged extraction times. Oxidative degradation can occur if oxygen exposure is not controlled (55).

Advanced and Green Extraction Methods

Advanced extraction technologies such as **ultrasound-assisted extraction (UAE)** and **enzyme-assisted extraction** have shown improved yields and reduced processing time. UAE enhances solvent penetration and disrupts cell walls, allowing efficient release of anthocyanins and phenolic (56).

Subcritical water extraction and **pressurized liquid extraction** are emerging as environmentally friendly alternatives, enabling selective recovery of pigments without organic solvents. Post-extraction stabilization techniques, including **microencapsulation using malt dextrin or gum arabic**, are widely employed to protect pigments from degradation and improve shelf life (57).

Application Potential as a Natural Colourant

Açaí pigments are increasingly utilized as natural colorants in **functional beverages, dairy products, nutraceutical capsules, and cosmetic formulations**. Their intense purple hue and associated antioxidant activity offer a dual benefit not achievable with synthetic dyes (58).

However, challenges such as pH sensitivity, light instability, and batch variability remain significant. Research into encapsulation, co-pigmentation, and formulation strategies continues to enhance the industrial viability of açaí-derived pigments (59).

PROCEDURE FOR EXTRACTION OF ANTHROCYANIN IN ACAI BERRY

1. **Prepare the sample**: Use frozen acai pulp or dried powder. If using pulp, it should be thawed. For dried material, it can be used directly.
2. **Select a solvent**: Use a polar solvent such as methanol or ethanol. Adding a small amount of acid (e.g., formic, acetic, or citric acid) to the solvent mixture is recommended to increase anthocyanin solubility and stability.
3. **Mix and extract**: Combine the acai sample with the solvent in a ratio specified by your protocol (e.g., 0.05–0.025 g/mL).
4. **Apply extraction method**:
    a) **Maceration**: Stir the mixture for a specific period.
    b) **Ultrasound-assisted extraction (UAE)**: Place the sample in an ultrasonic bath for a set time (e.g., 10 minutes) at a specific amplitude.
5. **Separate and filter**: Centrifuge the mixture or allow the solids to settle. Carefully decant the liquid extract. Filter the liquid to remove any remaining solids, using a filter with a small pore size (e.g., 0.22 µm).
6. **Protect from light**: Immediately protect the final extract from light to prevent degradation of the anthocyanins.

Walnut (*Juglans regia*)

Fig 3: WALNUT (Juglans)

Botanical Background and Source of Pigments

Walnut (*Juglans regia* L.) is a deciduous tree belonging to the family Juglandaceae, widely cultivated across Europe, Asia, and parts of the Americas. While the edible kernel is primarily valued for its nutritional oil, the green husk, shell, and bark are rich sources of natural pigments and bioactive compounds. Historically, walnut husk extracts have been used as natural dyes for textiles, hair coloring, leather tanning, and wood staining (60).

The pigmentation potential of walnut is mainly associated with the presence of naphthoquinone derivatives, which impart brown to dark reddish hues and exhibit strong binding affinity toward proteins and cellulose fibers (61).

Pigments in Walnut

The principal pigment present in walnut husk is jug lone (5-hydroxy-1, 4-naphthoquinone), a bioactive compound responsible for the characteristic brown coloration. Juglone is synthesized via the shikimate pathway and accumulates predominantly in the green husk and roots. In addition to jug lone, walnut husks contain tannins, flavonoids, and phenolic acids that contribute to color depth and fastness (62).

Juglone exhibits strong chromophoric properties due to its conjugated quinone structure, allowing effective interaction with textile fibers without the need for heavy mordanting. However, its high reactivity also contributes to allelopathic and antimicrobial effects (63).

Table 4: Taxonomy of Walnut (Juglans)

TAXONOMICAL CLASSIFICATION	
Kingdom	Plant
Subkingdom	Viridinplantae
Super division	Spermatophyta (seed plants)
Division	Juglandaceae
Class	Dicotyledonae
Order	Fagales
Genus	Juglans
Family	Juglandaceae
Species	English Walnut

Oil Composition of Walnut Kernel

Walnut kernel oil is recognized for its exceptional nutritional and functional properties. The oil is rich in polyunsaturated fatty acids, particularly linoleic acid (ω-6) and α-linolenic acid (ω-3), which together account for over 70% of the total fatty acid content. Monounsaturated oleic acid and saturated palmitic and stearic acids are present in smaller amounts (64).

In addition to fatty acids, walnut oil contains tocopherols, phytosterols, squalene, and phenolic compounds, which contribute to oxidative stability and health-promoting properties. These minor components are highly sensitive to heat and chemical processing, making extraction technique a critical determinant of oil quality (65).

Cold Press Extraction of Walnut Oil

Principle and Process

Cold press extraction is a **mechanical oil recovery technique** that involves pressing walnut kernels without the application of external heat or chemical solvents. The process begins with cleaning and drying the kernels to optimal moisture levels, followed by crushing and mechanical pressing using screw or hydraulic presses. Oil is released through pressure, while the residual solid material forms a press cake (66).

Throughout the process, temperature is maintained below 40–45 °C to preserve thermolabile bioactive compounds. The extracted oil is then subjected to sedimentation, centrifugation, or filtration to remove suspended solids (67).

Advantages of Cold Press Extraction

Cold pressing preserves the **natural chemical integrity** of walnut oil by minimizing thermal degradation and oxidation. Oils obtained through this method retain higher concentrations of tocopherols, phenolic antioxidants, and volatile compounds compared to solvent-extracted or refined oils. Additionally, the absence of organic solvents makes cold-pressed oil suitable for food, cosmetic, and pharmaceutical applications (68).

From an environmental perspective, cold pressing is considered a **green and sustainable extraction method**, producing minimal waste and eliminating solvent disposal issues (69).

Limitations and Optimization Parameters

Despite its advantages, cold press extraction typically yields **lower oil recovery** than solvent-based methods. Key parameters influencing efficiency include kernel particle size, moisture content, press speed, and applied pressure. Improper control of these variables can lead to excessive oil retention in the press cake or increased oxidative degradation (70).

Fig 4: Graphical presentation of cold oil extraction process

To enhance yield while maintaining quality, pre-conditioning strategies such as mild roasting or enzymatic treatment have been explored; however, these must be carefully optimized to avoid compromising bioactive constituents (71).

Bioactivity of Walnut Pigments and Oil

Juglone and related phenolic compounds exhibit **antimicrobial, antifungal, antioxidant, and anticancer activities**. The antimicrobial activity of juglone is attributed to its ability to generate reactive oxygen species and disrupt microbial cell membranes and enzyme systems (72).

Walnut oil consumption has been associated with **cardio protective, anti-inflammatory, and neuroprotective effects**, largely due to its favourable fatty acid profile and antioxidant content. Clinical and epidemiological studies suggest that regular intake of walnut oil may reduce oxidative stress and improve lipid metabolism (73).

Application of Walnut Pigments as Natural Colourants

Walnut husk extracts are widely used as **natural brown dyes** in textile and cosmetic applications. The dye exhibits good affinity for natural fibers such as wool, cotton, and silk, often requiring minimal mordanting. Iron salts deepen the shade, while alum produces lighter brown tones (74).

In addition to textile dyeing, walnut pigments are employed in hair dyes, wood stains, and eco-friendly inks. The combination of colorant functionality with antimicrobial properties enhances their value in sustainable product development (75).

Significance and Industrial Prospects

Walnut represents a unique plant resource where **both pigment-rich waste materials (husks)** and **high-value oil** can be simultaneously utilized. Valorisation of walnut by-products aligns with circular economy principles and reduces agricultural waste. With improved extraction technologies and standardization, walnut-derived pigments and oils hold strong potential for expansion in natural colorant and nutraceutical markets (76).

Saffron (*Crocus sativus*)

Botanical Background and Economic Importance

Saffron is derived from the dried stigmas of *Crocus sativus* L., a perennial herb belonging to the family **Iridaceae**. The plant is sterile and propagated exclusively through corms, making saffron cultivation labour-intensive and geographically restricted to regions such as Iran, India (Kashmir), Spain, Greece, and parts of North Africa. Due to the low yield of stigmas per flower and manual harvesting requirements, saffron is considered the **most expensive spice in the world** (77).

Beyond its culinary value, saffron has been historically prized as a **natural colorant, medicinal agent, and aromatic substance**, with documented use dating back to ancient Persian, Ayurvedic, and Greco-Arab systems of medicine (78).

Fig 5: Saffron (Crocus Sativus)

Pigments of Saffron: Crocin, Picrocrocin, and Safranal

The characteristic color, taste, and aroma of saffron are attributed to three major apocarotenoid compounds: **crocin, picrocrocin, and safranal**. Among these, crocin is the principal pigment responsible for saffron's intense golden-yellow coloration. Chemically, crocin consists of crocetin esterified with gentiobiose sugar moieties, which uniquely confers water solubility to a carotenoid-derived compound (79).

Picrocrocin is a monoterpene glycoside responsible for saffron's bitter taste and serves as the biochemical precursor of safranal. During drying and storage, picrocrocin undergoes enzymatic and thermal degradation to form safranal, the primary volatile compound contributing to saffron's aroma (80).

Table 5: Taxonomy and common name of Saffron (Crocus sativus)

TAXONOMICAL CLASSIFICATION	
Kingdom	Plantae (Plants)
Phylum	Tracheophyta / Magnoliophyta
Class	Liliopsida / Monocotyledonae
Order	Asparagales / Liliales
Family	Iridaceae (Iris family)
Genus	Crocus
Species	Crocus sativus

Chemistry and Stability of Crocin

Crocin exhibits strong chromophoric properties due to its extended conjugated double-bond system. Unlike many carotenoids, crocin is highly soluble in water, enabling its use in aqueous food systems and pharmaceutical formulations. However, crocin is sensitive to **light, heat, and oxidative conditions**, leading to gradual degradation and loss of color intensity during storage (81).

The stability of crocin is influenced by factors such as pH, temperature, and exposure to oxygen. Encapsulation techniques and controlled drying processes have been shown to significantly improve pigment retention and shelf life, making crocin suitable for commercial applications as a natural colorant (82).

Preparation and Processing Stages of Saffron

The preparation of saffron involves several critical stages that directly influence pigment content and quality. Harvesting is performed during early morning hours to minimize photodegradation of pigments. Fresh flowers are manually collected, and stigmas are carefully separated to avoid contamination with floral tissues (83).

Drying is the most crucial processing step, as it determines the conversion of picrocrocin to safranal while preserving crocin content. Traditional sun drying, hot-air drying, and modern controlled dehydration techniques are employed, with temperature and duration optimized to achieve maximum color strength without excessive pigment degradation (84).

Post-drying, saffron is stored in airtight, light-resistant containers under low humidity to maintain chemical stability. International quality standards classify saffron based on crocin, picrocrocin, and safranal content measured spectrophotometrically (ISO standards) (85).

PHARMACOLOGICAL ACTIVITY

Antitussive Activity

Saffron has been traditionally used as a remedy for respiratory ailments, particularly cough and bronchial irritation. Experimental studies suggest that crocin and safranal exert **central and peripheral antitussive effects**, possibly through modulation of neurotransmitter pathways and relaxation of bronchial smooth muscles (86).

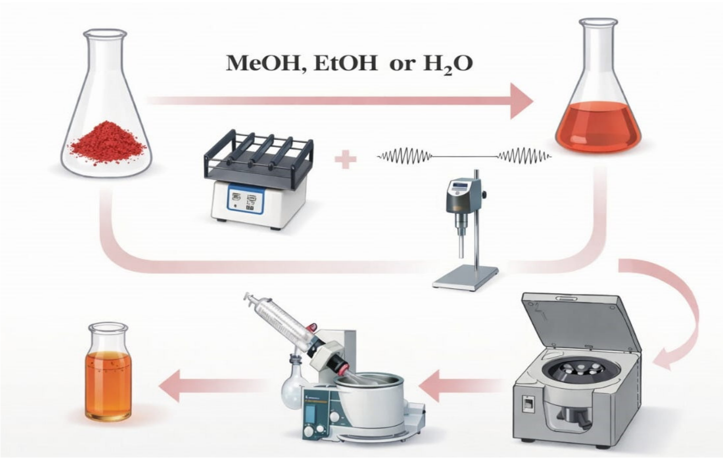

Fig 6: Preparation and Processing Stages of Saffron

Antihypertensive Activity

Several preclinical studies have demonstrated the **blood pressure–lowering effects** of saffron and its constituents. Crocin and crocetin promote vasodilation, improve endothelial function, and reduce oxidative stress in vascular tissues. These effects collectively contribute to improved cardiovascular function and reduced hypertension risk (87).

Antidiabetic Activity

Saffron extracts have shown promising **antidiabetic effects** in animal models by enhancing insulin sensitivity, reducing oxidative stress, and modulating glucose metabolism enzymes. Crocin has been reported to lower fasting blood glucose levels and improve lipid profiles, supporting its potential role as an adjunct therapy in metabolic disorders (88).

BROADER PHARMACOLOGICAL SIGNIFICANCE

In addition to the activities mentioned above, saffron exhibits **antioxidant, anti-inflammatory, neuroprotective, antidepressant, and anticancer properties**. These effects are primarily attributed to crocin and crocetin, which modulate inflammatory mediators, inhibit lipid peroxidation, and protect neuronal cells against oxidative damage (89).

Clinical studies, although limited in scale, support the therapeutic potential of saffron in mood disorders and cognitive impairment. However, standardized dosing and long-term safety evaluations remain necessary for pharmaceutical translation.

SAFFRON AS A NATURAL COLOURANT

Saffron has long been used as a natural colorant in food, textiles, and cosmetics. Crocin provides a stable and vibrant yellow hue, particularly suitable for aqueous systems such as beverages, dairy products, and herbal formulations. Compared to synthetic yellow dyes, saffron-derived pigments offer superior safety and added health benefits, albeit at a higher cost (90).

Advances in extraction, purification, and encapsulation technologies are expected to enhance the feasibility of saffron pigments as high-value natural colorants in specialized applications.

DISCUSSION

This review highlights the growing importance of bioactive plant pigments as natural colourants with added therapeutic value. Pigments such as anthocyanins, carotenoids, and quinones derived from hibiscus, açaí berry, walnut, and saffron demonstrate significant antioxidant, antimicrobial, and metabolic regulatory activities in addition to their coloring properties. These multifunctional characteristics make plant pigments attractive alternatives to synthetic dyes in food, pharmaceutical, cosmetic, and textile applications.

Extraction techniques play a critical role in determining pigment quality and biological efficacy. While conventional solvent-based methods remain widely used, advanced extraction approaches such as ultrasound-assisted extraction, microwave-assisted extraction, and cold press extraction offer improved efficiency and better preservation of bioactive compounds. Despite these advancements, challenges related to pigment stability, standardization, and large-scale industrial application persist. Addressing these limitations through optimized extraction, formulation strategies, and quality control measures is essential for the successful commercialization of plant-based natural colourants.

CONCLUSION

Bioactive plant pigments represent a valuable class of natural colourants that combine aesthetic appeal with therapeutic functionality. The present review highlights that pigments derived from hibiscus, açaí berry, walnut, and saffron possess diverse chemical structures and exhibit significant antimicrobial, antioxidant, antidiabetic, antihypertensive, and respiratory benefits. Advances in extraction technologies have enhanced pigment recovery and stability, making natural colourants increasingly viable alternatives to synthetic dyes. Although challenges related to stability, standardization, and scalability remain, ongoing research and technological innovations are expected to overcome these barriers. The use of plant-based pigments aligns with global sustainability goals and offers promising opportunities for application in food, pharmaceutical, cosmetic, and textile industries. Therefore, bioactive plant pigments hold strong potential as safe, eco-friendly, and multifunctional agents for future industrial and therapeutic use.

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