

Plant Pigments: Science of Exploring the Spectrum

Plant pigments are vital molecules, responsible for the various colours in the plant kingdom, mainly chlorophyll, carotenoids, anthocyanins and betalains. Chlorophyll, being green in colour, is a principal pigment, as it is directly involved in photosynthesis by capturing light energy, whereas carotenoids, ranging from yellow to red in colour, are considered accessory pigments and also aid in light harvesting and energy transfer; thus, both are crucial for photosynthesis. Anthocyanins contribute to red, purple and blue colour, which depend on pH, molecular structure and presence of metal ions. These vibrant colours attract pollinators, important for the reproduction and dispersal of plant seeds and are beneficial in scavenging reactive oxygen species (ROS). Pigments are not only vital for plants, but also for humans, as they possess anti-inflammatory, anti-obesity, anti-allergic and anti-cancerous properties and reduce skin pigmentation. Also, they are precursor for vitamin synthesis; thus, pigments are very important. Moreover, plant pigments are also gaining interest in technological aspects, predominantly in dye-sensitised solar cells, where they offer an environment friendly alternative to conventional solar cells. Diverse applications of plant pigments highlight their enormous potential to boost creativity and environmental responsibility across multiple sectors, including agriculture, food, nutraceuticals, textiles, animal feeds and technology.

Keywords: Anthocyanins, Betalains, Carotenoids, Plant Pigments

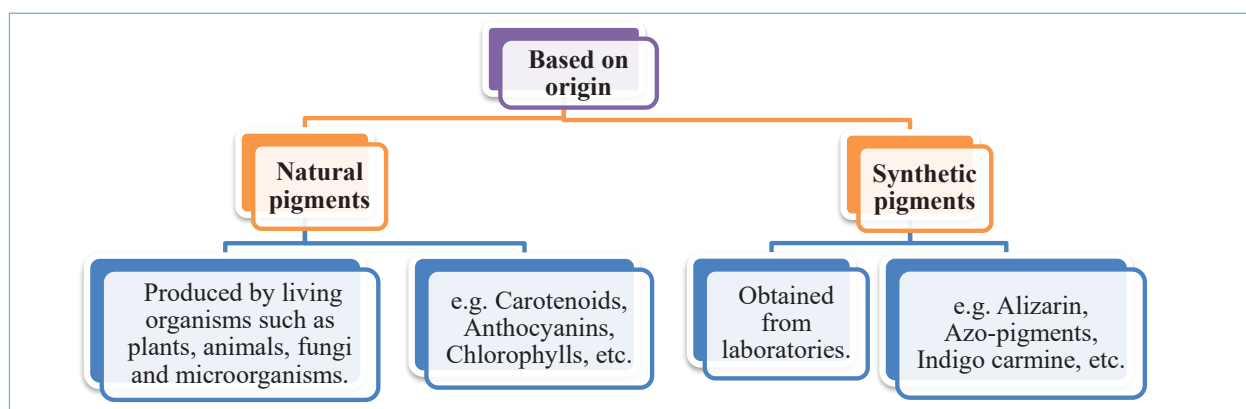
FLOWERS captivate the human mind with vibrant colours and make the world more magnificent. These colour depicting compounds are known as pigments. These pigments are not only restricted to flowers, they are also present in leaves, vegetables, fruits, etc. Fundamentally, pigments are chemical compounds that selectively absorb or reflect light in the visible range of wavelength (380–730 nm) and are crucial for the biological functioning of flowering plants. When visible light strikes the pigment molecule (chromophores)

at a particular wavelength, it absorbs the energy, which causes the excitation of electrons to a higher energy state, that is dissipated and utilised inside the plant in various ways, however, non-absorbed energy is reflected back and depicts the colour.

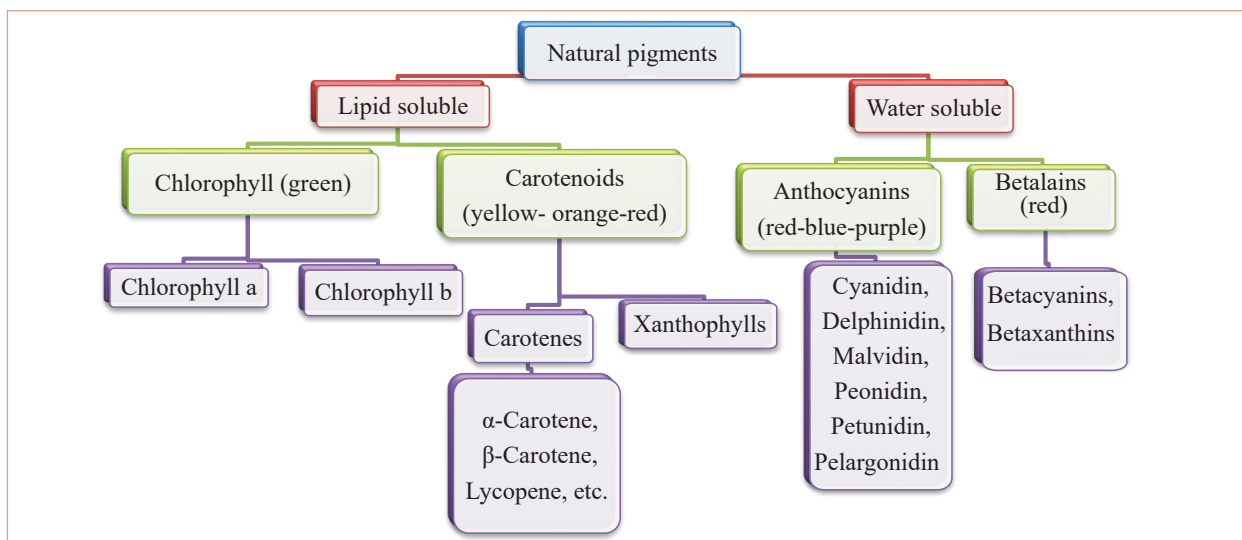
CLASSIFICATION OF PIGMENTS

Pigments are classified on several basis

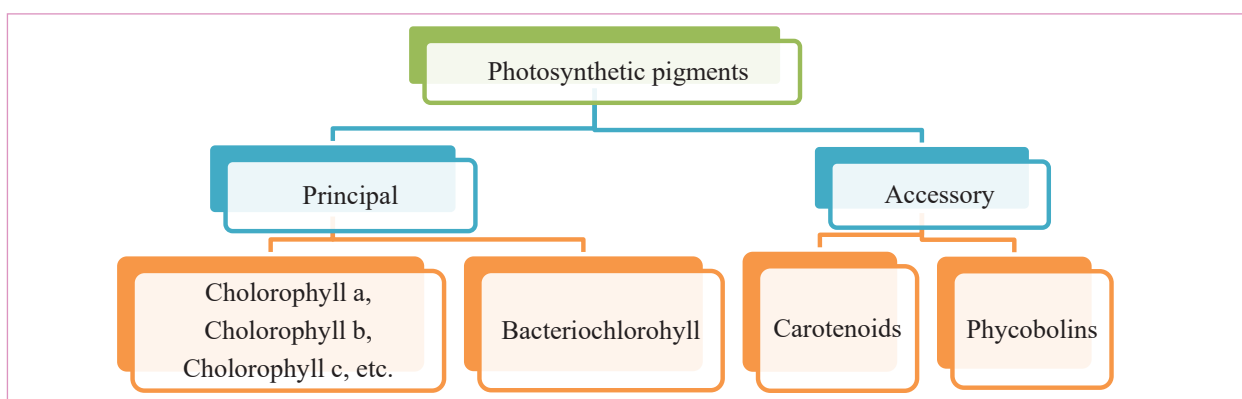
- *Based on origin:* Pigments can be naturally originated



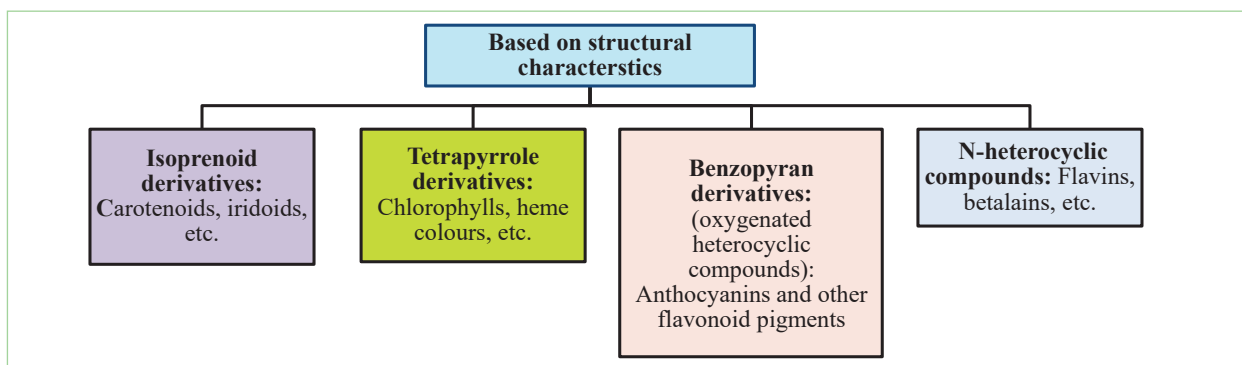
Classification of pigments based on origin



Classification of natural pigments based on solubility



Classification of pigments based on structural characteristics



Classification of photosynthetic pigments

inside living organisms as inside plants, fungi, animals, etc. On the other hand, they can also be synthesised artificially in lab.

- Further, natural pigments are classified on the basis of solubility.
- *Based on structural characteristics:* Pigments can also be classified on the basis of their structural characteristic.
- *Photosynthetic pigments:* The process of photosynthesis is a biochemical process through which light energy is converted into chemical and crucial for existence of life on the earth and it is impossible without pigments, as pigments are required for light harvesting for photosynthesis.

Photosynthetic pigments can be further elaborated under the following heads

A. *Chlorophyll:* The life on earth directly or indirectly depends on a vital plant pigment known as chlorophyll which is predominantly green in colour. Chemically, chlorophyll is comprised of tetra pyrrole ring with a central magnesium ion. It is hydrophobic in nature and strongly absorbs blue and red light of electromagnetic spectrum, however, poor absorber of green to near-green, thus depicts green colour. It is located in chloroplast of mesophyll cells and is directly involved in photosynthesis, thus known as principal pigment.

Function of chlorophyll: The main function of chlorophyll is photosynthesis, where the molecules of chlorophyll

absorb light energy in blue to red region of electromagnetic spectrum and cause excitation of electrons. Further, the excited electrons flow through a series of electron carriers and participate in light-dependent reactions that help in production of chemical energy in the form of ATP.

B. *Carotenoids*: Carotenoids are also hydrophobic and fat-soluble compounds made up from condensation of eight isoprene unit-terpenoid. They are found in plants, algae, bacteria and fungi and colours range from yellow to red. However, they are also present in non-photosynthetic organisms. They are accessory pigments and important for photosynthesis. Carotenoids are further classified into:

(i) *Carotene*: Unsaturated hydrocarbon consists of carbon and hydrogen atoms and colour ranges from orange to red. e.g. β -carotene in orange, carrots, etc.

(ii) *Xanthophyll*: Consists of carbon, hydrogen and one

or more additional oxygen atoms, colour ranges from yellow to orange. e.g. lutein in marigold, etc.

Functions of carotenoids

- They provide colours to fruits, flowers, vegetables and seeds; thus, attract pollinators and are important for reproduction.
- They are considered as accessory pigments and aid in light harvesting process of photosynthesis.
- They also protect photosynthetic system by dissipating the excess energy and prevent the formation of reactive oxygen species and control photo-oxidative damage.
- Carotenoids, such as β -carotene are precursors of vitamin A.

Different kinds of carotenoids and their origin from horticultural crops are given in Table 1.

Table 1. Different kinds of carotenoids and their origin from horticultural crops

S.No.	Carotenoids	Colour	Examples
1.	Lycopene	Red	 Tomatoes 0.88-4.20 mg/100 g Papaya 2.00-5.30 mg/100 g Water melon 2.30-7.20 mg/100 g
2.	Lutein	Yellow	 Spinach 7.043 mg/100 g Kale 39.55 mg/100 g Marigold 17-570 mg/100 g
3.	α -Carotene	Yellow	 Orange capsicum 0.89 mg/100 g Pumpkin 0.83-4.2 mg/100 g Carrot 2.5-4.9 mg/100g
4.	β -Carotene	Orange	 Carrot 8.29 mg/100g Apricot 1.09 mg/100 g Rose hips 2.984 mg/100 g

5.	β -Cryptoxanthin	Orange			
			Pumpkin 0.589 mg/100 g	Butternut squash 3.471 mg/100 g	Persimmon 1.447 mg/100 g
6.	Zeaxanthin	Yellow-orange			
			Broccoli 1.73628mg/100 g	Orange 0.24497 mg/100 g	Brussels sprouts 1.0062 mg/100 g
7.	Violaxanthin	Yellow			
			Lettuce 2.7 mg/100 g	Fenugreek leaves 4.62 mg/100 g	Moringa leaves 3.7 mg/100 g

C. Anthocyanin: Anthocyanin is a Greek word where, *anthos* means flower and *kyanos* means blue. It is a water-soluble phenolic compound which belongs to flavonoids, synthesised in the cytosol and stored in vacuoles. The structure consists of two aromatic rings linked by three carbon atoms forming an oxygenated heterocyclic ring. The precise colour of anthocyanins depends on numerous factors such as *pH*, molecular structure and presence of metal ions. If numerous OH groups are present, the colour shifts toward blue, however, more OCH₃ groups lead to red colour.

- *pH*: Anthocyanins are highly affected by *pH*, as it changes the ionisation state of the compounds and its ability to absorb light differently. In general:
 - Acidic conditions: colour appears red.

- Neutral *pH* to slight alkaline: colour shifts towards purple and blue.
- Metal ions: Presence of different metal ions i.e., magnesium, aluminum and iron form complexes with anthocyanins, thus change the colour. For instance, presence of aluminum ions can shift the colour red, whereas magnesium ions can intensify blue colour.
- Anthocyanins are further classified as cyanidin, delphinidin, malvidin, peonidin, petunidin and pelargonidin based on the specific anthocyanidin molecule. Different kinds of anthocyanins and their origin from horticultural crops are given in Table 2.

Functions of anthocyanins

- Attract pollinators by making flowers more appealing

Table 2. Different kinds of anthocyanins and their origin from horticultural crops

S.No.	Anthocyanin	Colour	Examples
1.	Cyanidin	Red (acidic) purple (neutral) blue (alkaline)	  
			Sweet cherries 18.73 mg/100 Strawberries 2.88 mg/100 Plum 8.63 mg/100 g

2.	Delphinidin	Blue (acidic) violet (neutral) purple (alkaline)			
			Blackcurrant 86.68 mg/100	Blueberries 8.08 mg/100 g	Black grapes 16.61 mg/100 g
3.	Malvidin	Red (acidic) purple (neutral) blue (alkaline)			
			Blueberries 11.18 mg/100	Black grapes 39.23 mg/100 g	Raspberry 0.62 mg/100 g
4.	Peonidin	Red to purple			
			Plum 0.46 mg/100 g	Cranberries 4.16 mg/100 g	Grapes 5.80 mg/100 g
5.	Petunidin	Purple to blue			
			Blueberries 11.20 mg/100 g	Grapes 2.76 mg/100 g	Blackcurrant 3.87 mg/100 g
6.	Pelargonidin	Red (acidic) orange to pink (slightly alkaline)			
			Strawberries 47.14 mg/100 g	Raspberries 1.65 mg/100 g	Pomegranate 0.46 mg/100 mL

and vibrant, thus vital for reproduction and seed production.

- When co-occurred with other pigments i.e. chlorophyll, carotenoids, etc. leads to petal pigmentation.
- They screen harmful UV radiations and protect plant tissues from damage.
- They are source of antioxidants, which neutralise free radicals scavenge reactive oxygen species and reduce oxidative stress.
- They are produced in response to various biotic and abiotic stresses i.e. excess light intensity, low temperature, nutrient deficiencies and certain infections.

D. **Betalains:** Betalains are nitrogen containing, indole-derived compounds, synthesised by tyrosine with the condensation of betalamic acid. They are water soluble pigments, present in vacuole of cells and present in various parts of plants i.e. dragon fruit, roots of beetroot, flowers of celosia, bougainvillea, portulaca, etc. They are mainly

present in species of order Caryophyllales. They are independent of pH, more stable than anthocyanins and commercially used as source of dye in food.

Functions of betalain

- They are strong antioxidants, possess free radical scavenging properties and protect cells from oxidative stress.
- They can absorb excess UV radiations, protecting tissues from damage.
- Bright colour attracts pollinators and aids in the plant reproduction.

Pigments are not only meant for metabolic activities of plants, but also essential for human body due to several reasons such as:

- Possess antioxidants properties that shield the cells from damage by free radicals and lower the chances of chronic diseases.
- Some pigments such as beta-carotene are precursors

Table 3. Examples of betalains containing plant parts

Beetroot (root)	Dragon fruit (fruit)	Prickly pear (fruit)
Betacyanin = 30–60 mg/100 g Betaxanthin = 16.3 mg/100 g	Betacyanins = 73 mg/100 g	Betacyanins = 13.4 mg/100 g Betaxanthin = 24.3 mg/100 g
		
Amaranth (leaves)	Portulaca (flower)	Bougainvillea (bracts)
Betacyanins = 237 mg/100 g	Betalain = 26.6 mg/100 g	Betaxanthin = 249.5 mg/100 g Betacyanins = 145 mg/100 g
		

Table 4. Versatile applications of plants pigments in various fields

Health and nutrition	<i>Chlorophyll:</i> Detoxification properties and source of magnesium. <i>Carotenoids:</i> Vital for vision and immune function, reduce the risk of cancer and heart diseases. <i>Flavonoids:</i> Possess antioxidants and anti-inflammatory properties. <i>Betalains:</i> Contains detoxification, antioxidants and anti-inflammatory properties.
Pharmaceutical	<i>Chlorophyll:</i> Antioxidant, wound healing, detoxification, anti-inflammatory, etc. <i>Carotenoids:</i> It can lower the danger of breast, ovarian, gastrointestinal, pancreatic, cervical and colorectal cancers, prevent cardio-vascular disease and treat certain eye diseases. <i>Anthocyanins:</i> Anti-inflammatory, cardiovascular protection, prevent cancer by inhibiting cancer cell growth, lower cholesterol and combat oxidative stress. <i>Betalains:</i> Prevent hypertension, dyslipidemia and vascular stenosis, promotes liver health.

Cosmetics	Makeup products: Eye-shadows, lipsticks, nail polish, blushes, etc. Skin care: Pigments possess UV protection, anti-aging and moisturising properties, thus are added into certain skin care products. Hair care: Natural hair dye with the use of henna (<i>Lawsonia inermis</i>) and indigo, also used in conditioning of hairs.
Animal feed	<i>Carotenoids</i> : Improves the colour of egg yolks, chicken and fish flesh, thus enhance marketability. Also, improve milk quality in mammals. <i>Anthocyanins and xanthophylls</i> : Improve colour in fish i.e. trout and salmon.
Textiles	Plant based natural dyes are used for colouring the fabrics. Most used plants for dyeing fabrics are: (i) Indigo (<i>Indigo feratinctoria</i>): Blue tone. (ii) Henna (<i>Lawsonia inermis</i>): Orange and red tones. (iii) Madder (<i>Rubia tinctorum</i>): Red hues. (iv) Turmeric (<i>Curcuma longa</i>): Yellow shades. (v) Chlorophyll: Green tone, etc.
Technology	Plant based natural pigments are also incorporated into the solar cell structure to absorb sunlight and facilitate in the production of low cost 'Dye-sensitised solar cells' Plants used for production of dye-sensitised solar cells are: (i) <i>Cochlospermum religiosum</i> (ii) <i>Rhododendron arboretum</i> (iii) <i>Perilla frutescens</i> , etc.

- of vitamins A, thus are vital for vision and immunity.
- Possess anti-inflammatory properties that can reduce the risk of cardiovascular conditions.
- Possess anti-obesity, anti-allergic and anti-cancerous properties, also encounters reactive oxygen species in human body and also used as anti-aging supplements.
- Enhances oxygen intake inside human body and helps in recovering deficiencies.
- Reduce skin pigmentation and help in detoxifying body.

SUMMARY

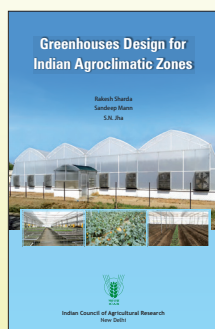
The diverse plant pigments are not only responsible for aesthetic vibrant colours, but are also crucial for bio-chemical functioning of plants. From harvesting of light for photosynthesis to protecting cells from excess light and oxidative stress, they are essential for growth, development and reproduction of plants. The proportion of these pigments inside plants are determined by

developmental stages, genetic factors and environmental circumstances, thus serving as valuable markers of stress responses and plant health. Further, the versatile nature of pigments has far-reaching applications beyond their aesthetic beauty, playing an imperative role in influencing advancements across a variety of industries including agriculture, food and nutraceuticals. Furthermore, plant pigments are employed in dye-sensitised solar cells, providing a sustainable energy source. Overall, the diverse applications of plant pigments illustrate their expanding influence on innovation and sustainability, necessitating renewed scientific research.

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