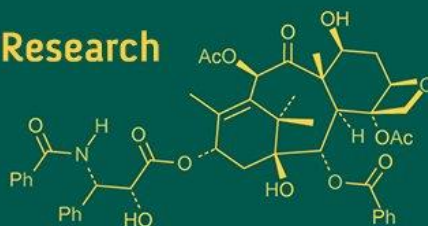


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Natural dyes: Sustainability, extraction methods and recent innovations

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Abstract

Natural dyes, obtained from plants, animals, and minerals, have played a vital role in human civilization for thousands of years. Their eco-friendly, biodegradable nature and cultural significance have initiated resurgence in recent decades and re-establishing as sustainable alternatives to synthetic dyes. Owing to non-polluting, non-carcinogenic, and environmentally friendly properties, natural dyes have gained global prominence. The present study synthesizes historical perspectives, classification of natural dyes, extraction techniques, where rigorously assessing their ecological benefits and industrial applications. Recent innovations containing plasma technique, ultrasonic process and microwave-assisted technologies have strengthened dyeing efficiency, although biotechnology approaches allow pigment production through microorganisms, minimizing dependence on traditional resources. Utilization of agricultural and industrial waste into dyeing processes enhances circular economy models and sustainability. Continued research, technological advancement, and standardization are essential to synthesize their role as viable, scalable, and environmentally responsible alternatives in global textile and fashion industries.

Keywords: Natural dyes, sustainability, extraction methods, ecological benefits, biodegradable

Introduction

India has a very rich tradition of using natural dyes. Natural dyes are colourants derived from natural sources such as plants, animals, and minerals. Known for their rich, earthy tones and eco-friendly properties, these dyes have been used for centuries in textile colouring, art, and other applications (Saxena and Raja, 2014) [34]. Synthetic dyes dominate the global textile industry but pose serious environmental and health concerns due to toxic effluents and non-biodegradable residues. Many of the synthetic dyes have been banned in many countries and dye industries are now looking towards substituent natural dyes (Yadav *et al.*, 2023) [42]. Natural dyes generate incredibly unique, soothing, fantastic, tonally rich, and soft colours when compared to synthetic dyes. Natural dyes are typically non-substantive to the fabric being dyed in most cases, and their colour could be enhanced if the cloth is first treated with metallic salts like iron, copper, or tin salt. (Broadbent, 2001; Ebrahim *et al.*, 2022; Ragab *et al.*, 2022) [4, 10, 29]. A further mordanting step is often required, making the process a two-stage procedure. In this method, mordants, typically metallic salts are employed due to their affinity for both the colouring component and the fiber. Natural dyes are biodegradable, non-toxic, and culturally significant. The current study is deliberate their origin, chemistry, application methods, and ecological relevance, while assessing their potential role in sustainable textile production.

Origin of natural dyes

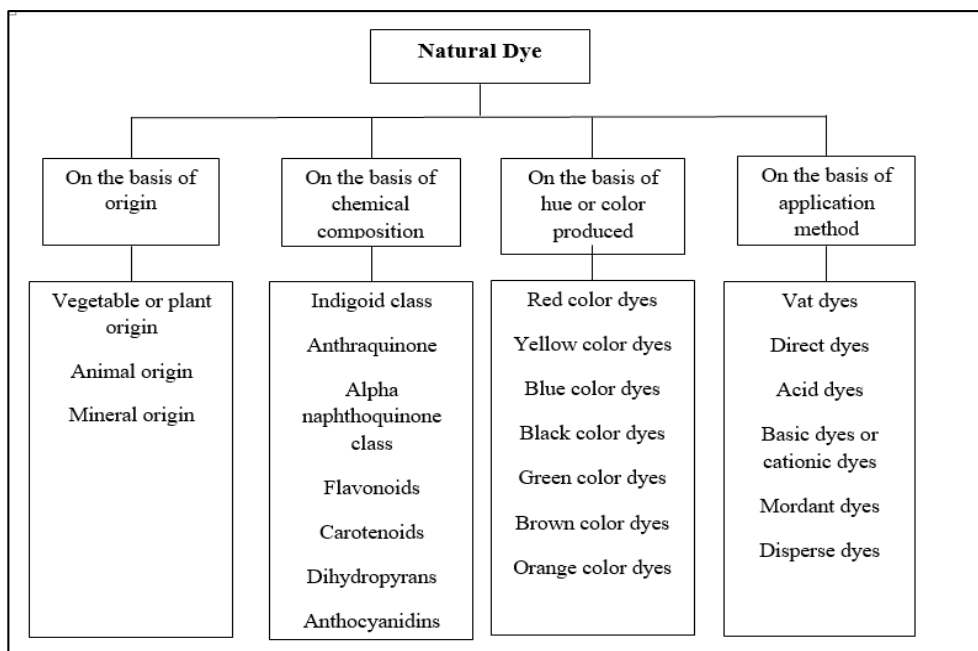
The first natural dye was found around 2600BC. Originally, dyes were made with natural pigments mixed with water or oil as a base. The art of dying fabrics has been an integral part of human civilization. Over 4000 years, since ancient Egypt to the present, people have been using various dyes to brighten clothes (Alegbe and Uthman, 2024; Bishal *et al.*, 2023) [2, 3]. Chemical tests of red fabrics found in the tomb of King Tutankhamun in Egypt show the presence of alizarin. The famed *Indigofera tinctoria* plant was cultivated for blue dye, while cochineal insects were harvested in Central and South America for red pigment. Natural dyes were highly valued, often symbolizing status and wealth.

Historical milestones include

- The discovery of madder root (*Rubia tinctorum*) for producing red hues in ancient Egypt.
- The use of turmeric and henna in India for textiles and body art.
- Tyrian purple, extracted from sea snails, becoming a symbol of royalty in the Roman Empire.

Classification of natural dyes

Different natural sources can be used to produce natural dyes. Different plant parts, such as the roots, bark, leaves, flowers, and fruit, can produce a broad variety of hues (Uddin, 2013) ^[38]. They can also be originated from insect source, mineral sources, and different waste sources.



1. Classification on the basis of origin

On the basis of their origin and occurring, natural dyes are classified into three distinct categories such as plant or vegetable dye, animal dye, and mineral dye (Dey *et al.*, 2025) ^[9].

i. Plant-based/vegetable-based sources

The majority of natural dyes have been extracted from plants or vegetables historically. In addition to roots, leaves, twigs, stems, bark, flowers, fruits, rinds, hulls, husks, and other plant parts, natural dyes also come from roots, leaves, twigs, stems, wood, bark and the like (Singh and Srivastava, 2015; Verma and Gupta, 2017) ^[35, 40]. There are over 450 dye-yielding plants and vegetables found in India. Indigo is a famous blue dye made from leaves of the plant *indigofera tinctoria*. Examples of natural dyes obtained from leaves, root, bark and flowers are given below:

- **Leaves:** Indigo (*Indigofera tinctoria*), henna (*Lawsonia inermis*).
- **Roots:** Madder (*Rubia tinctorum*), turmeric (*Curcuma longa*).
- **Barks:** Cutch (*Acacia catechu*), pomegranate bark (*Punica granatum*).
- **Flowers:** Marigold (*Tagetes erecta*), safflower (*Carthamus tinctorius*).

ii. Animal-based sources

Insects were the main source of natural dyes of animal origin and most of these provided red colours. Tyrian purple was the oldest animal source dye, obtained from the sea mollusc *Murex* secretions (Saxena and Raja, 2014; Ahsan *et al.*, 2020) ^[34, 1]. The best red dyes known to people in those early days were obtained from animals. Examples of natural dyes obtained from animal origin are given below:

Sr. No.	Animal	Botanical Name	Extracted Colour
a.	Cochineal insects	<i>Dactylopius coccus</i>	Brownish red
b.	Murex snails	<i>Muricidae murex</i>	Purple
c.	Octopus	<i>Octopus vulgaris</i>	Black
d.	Lace insect	<i>Kerria lacca</i>	Red
e.	Polish cochineal	<i>Porphyrophora polonica</i>	Red

iii. Mineral-based sources

Natural dyes with mineral origin include several colours derived from inorganic metal salts and metal oxides. Mineral dyes are classified based on the colour obtained. Some examples of natural dyes are given below:

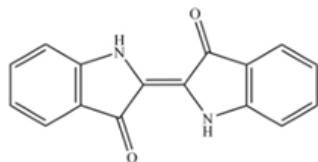
Sr. No.	Dyes Name	Extract Colour
a.	Ochre	Yellow, brown, red
b.	Malachite	Green
c.	Manganese	Black
d.	Cinnabar	Red
e.	Azurite	Blue
f.	Lead	Red
g.	Aragonite	White
h.	Lapis lazuli	Blue

2. Classification on the basis of chemical constitution

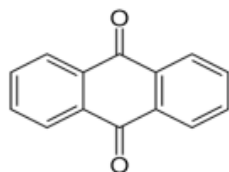
The natural dyes are classified on the basis of the chemical composition as follows:

i. Indigoid class

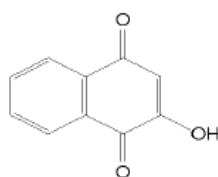
The important dyes in this class are the indigo blue and Tyrian purple, other blue dye in the class is the woad dye (*Isatis tinctoria*). Sources of indigo dyes are: *Isatis tinctoria*, *Perisicaria tinctoria*, and *Indigofera tinctoria* (Garcia-Macias and John, 2004, John, 2009) ^[11, 15].

Indigo (Vankar *et al.*, 2000; Mayur and Nainesh, 2020) [39, 21]**ii. Anthraquinone class**

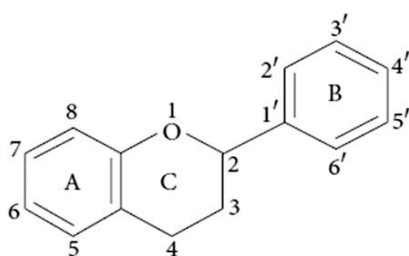
These have both plant and animal origin. These have the anthraquinone structure and contain hydroxyl or amino functional groups as their major auxochromes. Madder, kermes, cochineal and lacs are under this class (Vankar *et al.*, 2000; Mayur and Nainesh, 2020) [39, 21].

Anthraquinone (Vankar *et al.*, 2000; Mayur and Nainesh, 2020) [39, 21]**iii. α -hydroxyl-naphthoquinone class**

These have the α -naphthoquinone structure like 2-hydroxy 1,4-naphthoquinone. Examples are *henna*, madder etc.

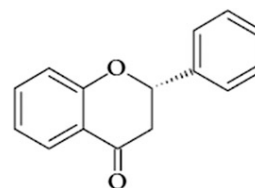
 α -hydroxy-naphthoquinone (Vankar *et al.*, 2000; Mayur and Nainesh, 2020) [39, 21]**iv. Flavonoid Dyes**

In botanic, flavonoids, known as colourific groups, are compounds synthesized by plants in phenolic structure (Kumar and Sinha, 2004) [18]. In medical, flavonoids are utilized as anti-inflammatory, anti-allergic, anti-tumor formation, anti-viral, anti-diabetic, cardiovascular protective, antioxidant, and antimicrobial (Marčetić *et al.*, 2013; Merdan *et al.*, 2016) [20, 22]. Flavonoids can be grouped into seven classes such as flavones, flavonols, isoflavones, anthocyanidins, anthocyanins, and proanthocyanidins.

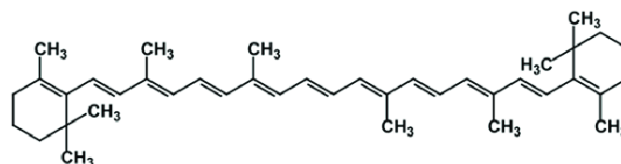
Flavonoid dyes (Merdan *et al.*, 2016) [22]

Flavones: The dyestuffs yield yellow colour. Most of the dyes in this class are derivatives of hydroxyl and methoxy substituted flavones or isoflavones. Examples are *tesu*, marigold, cutch etc.

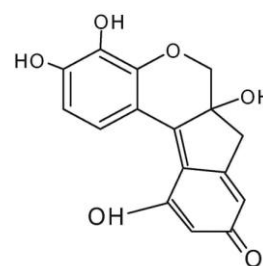
Furthermore, isoflavones are presented in pulses consisting soya. Moreover, bean, cacao, grape, apple, apricot, peach, cherry, blackberry, black tea, and green tea contain proanthocyanidin (Merdan *et al.*, 2016) [22].

Flavones (Merdan *et al.*, 2016) [22]**v. Carotenoids**

The dye structures in this class contain long chain conjugated double bonds. These double bonds act as chromophore and are responsible for characteristic absorption spectra. The colour in this group ranges from yellow, orange to red. Examples of dyes under carotenoid class are annatto, saffron. Source of dyes under carotenoids class are *Crocus sativus* (saffron), *Curcuma longa*, *Nyctanthes arbor-tristis*, *Cedrela toona*, and *Bixa orellana* (annatto) (Chandrika, 2009) [5].

 β -carotene (Mayur and Nainesh, 2020) [21]**vi. Dihydropyrans**

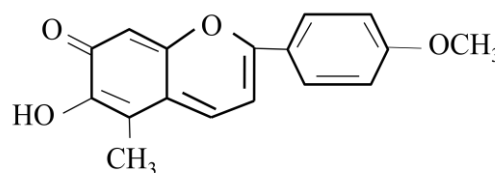
These dyes are made up of brazilin from brazilwood (*Caesalpinia sappan*) and haematoxylin from logwood (*Haematoxylon campechianum*).



Dihydropyrans (Vankar, 2000) [39]

vii. Anthocyanidins

This class provides shades of blue and orange.



Anthocyanidins

3. Classification on the basis of hue or colour produced

The classification of dyes on the basis of hue or colour produced is as follows:

i. Red colour dyes

The dyes are based on anthraquinone and its derivatives. These are mostly roots or bark of the plant or from the body of the insects. The dyes are stable to light and washing with a range from good to excellent. Examples are madder roots, Cochineal, Manjith and Kusumbar etc.

ii. Yellow colour dyes

Around 90% of yellow dyes are from flavonoids. Wash fastness of natural dyes ranges from fair to excellent. Examples are tesu, turmeric (*Curcuma longa*), Marigold (*Tagetes erecta*), Safflower (*Carthamus tinctorius*), Kamala (*Mallotus philippensis*) etc.

iii. Blue colour dyes

The blue colour natural dye is produced mainly due to the presence of indigoid. The examples are indigo (*Indigofera tinctoria*) and woad leaves (*Isatis tinctoria*), these give excellent fastness to light and washing.

iv. Black colour dyes

Black shades are produced from the leaves and barks of trees and shrubs which are rich in tannins, when combined with ferric or ferrous salts. In general, tannins in combination with various mordant salts yield a wide range of shades—brown, gray, reddish and black, all of which exhibit good colour fastness properties (Mongkhorrattanasit *et al.*, 2009; Punrattanasin *et al.*, 2013) [24, 28]. Examples are logwood, *harda*, custard apple, Catechu (*Acacia catechu*) etc.

v. Green colour dyes

These dyes are formed due to the combinations of yellow and blue dyes examples are Malachite, chlorophyll-based dyes.

vi. Brown colour dyes

Tannin rich oak galls are used as mordant in dyeing process. They are also a source of brown colour. Catechu or cutch acquired from the heartwood of *Acacia catechu* is applied to dye cotton, wool, and silk to give brown colour directly (Saxena and Raja, 2014) [34].

vii. Orange colour dyes

Annatto (*Bixa orellana*) is a small tree pertaining to the family Bixaceae. It is well-known for yellow orange dye acquired from its seed. It is widely utilized for the dyeing of cotton, wool, and silk. It provides reddish orange colour on cotton, wool, and silk (Saxena and Raja, 2014) [34].

Extraction methods of natural dyes

The extraction of natural dyes involves isolating pigments from raw materials. Common methods include:

i. Maceration

Raw materials (e.g., leaves, flowers, roots) are crushed or chopped and soaked in water or solvents at room temperature, allowing the dye to leach out. For example, pink pigments are extracted to soak rose petals in aqueous medium.

ii. Decoction

The dye source is boiled in water to release pigments. After boiling, the solution is strained to remove solid residues. By boiling of turmeric rhizomes, a yellow dye is obtained.

iii. Fermentation

The raw material is soaked in water and left to ferment naturally for several days. Microbial activity helps break down plant cell walls, releasing pigments. Indigo leaves are fermented to produce blue pigment (Chungkrang *et al.*, 2021) [6].

Organic solvents such as ethanol, acetone etc. are used to dissolve and extract pigments from the raw material, often using Soxhlet extractors. Extraction of carotenoids from marigold flowers is carried out using acetone as organic solvent.

iv. Enzyme-assisted extraction

Enzymes like cellulase or pectinase are used to break down plant cell walls, releasing pigments. Anthocyanins are obtained from blackcurrant skins through enzymatic extraction method.

v. Supercritical fluid extraction (SCFE)

Supercritical CO₂ or other fluids are used to extract pigments under high pressure and temperature. This method is used to extract lycopene (red pigment) from tomatoes.

vi. Ultrasonic-assisted extraction (UAE)

In this method, ultrasound waves are used to increase the efficiency of extraction. Ultrasound waves disrupt the plant cells, enhancing pigment release in a liquid medium (Mishra *et al.*, 2012; Rahman *et al.*, 2013; Pizzicato *et al.*, 2023) [23, 30, 27]. This method is employed for extraction of flavonoids from pomegranate peel.

vii. Microwave-assisted extraction (MAE)

Raw materials are exposed to microwave radiation, heating the moisture inside and releasing pigments. Betalains are extracted from beetroot by using microwave radiation.

Advantages of natural dyes

- Natural dyes are non-polluting.
- It supports traditional dyeing techniques and crafts.
- The naturally dyed colours are Soft, earthy, lustrous, unique colour tones and soothing to human eyes.
- Unlike the non-renewable resources used for synthetic dyes, vegetable-based natural dyes are both renewable and biodegradable (Samanta and Konar, 2012) [31]. They also save energy, as their raw materials are derived from plants instead of petroleum (Samanta *et al.*, 2018) [32].
- Many plants grow on wastelands, accomplishing wasteland utilization an added merit of natural dyes. For example, madder grows naturally as a host in tea gardens. Therefore, no additional cost or efforts are required for cultivation.
- Natural dye production is a labour-intensive industry (Patel *et al.*, 2002; Samanta *et al.*, 2018) [26, 32], providing employment opportunities in cultivation, extraction, and application processes. In addition, it can boost the textile exports and thus helping India earn valuable foreign exchange.
- Naturally dyed materials have good resistance to moths and possess anti-allergenic properties, making them safe for direct contact with the body and free of harmful chemicals like azo compounds.
- Natural dyes are mostly non-toxic and as a result non-hazardous to health.

- In addition, fabrics dyed with natural dyes can accommodate effective protection against ultraviolet (UV) rays without compromising their wear properties (Ibrahim *et al.*, 2010; Sun and Tang, 2011; Ibrahim *et al.*, 2013; Tamilarasi and Banuchitra, 2021) ^[12, 36, 13, 37].

Limitations of natural dyes

The high costs of natural dyeing arise from several factors. High cost is primarily due to their lower affinity for textile fibres, resulting in lower dye exhaustion from the dye bath onto the fibres. Natural dyes don't stick well to fibres, therefore, a much larger amount of dye is needed, and a large part of the dye remains in the dye bath, especially when trying to get dark colours. In addition, natural dyes and pigments occur in plants relatively in small quantities. On average, to dye one kilogram of fibres, it required one kilogram of dye plant material. This necessitates handling large amounts of biomass for obtaining them, leading to the generation of large quantities of waste. Disposal of this waste poses challenges, even though some plant-based dyeing residues can be repurposed as fertiliser or fuel. Furthermore, the cost of transporting bulky volumes of plant material from the harvesting site to the processing location further increases (Křížová, 2015) ^[17].

Wild plants collected from open nature are not suitable for large-scale industrial textile production. Many natural dyes are acquired from tree bark, wood, and roots, but harvesting them generally harms the plant. Utilizing timber industry by-products may be more sustainable, as yet cutting trees solely for dyeing is sure leads to deforestation. Use of flowers also disrupts pollination and reproduction. Also it is not effective on an industrial scale because they are not available in large quantities. Overall, such practices can cause substantial destruction to ecosystems, potentially making some plant species endangered (Saxena and Raja, 2014; Křížová, 2015) ^[34, 17].

Benefits of natural dyes for ecological system

1. **Pollution reduction:** Minimal use of synthetic chemicals and heavy metals. Also lesser water contamination during dyeing.
2. **Biodiversity conservation:** Promotes the cultivation of dye-yielding plants, enhancing agro forestry.
3. **Carbon footprint:** Lower energy consumption compared to synthetic dye production.

Recent innovations and trends in natural dyes

1. Use of agricultural and industrial waste

Utilizing by-products such as pomegranate peels for yellow and orange tones, onion skins for earthy browns and walnut shells for deep browns and blacks. Reduces waste while providing sustainable raw materials for dyes (Joshi *et al.*, 2020; Devi *et al.*, 2025) ^[16, 8].

2. Integration into circular economy models

Encouraging dye sources from renewable resources that fit circular economy principles. For example growing of dye plants alongside food crops in regenerative farming systems. It also utilizing by-products from the agricultural and timber industries, such as peels, husks, and bark as dye sources to minimize waste (Yadav *et al.*, 2025) ^[41] and promotes sustainable biomass utilization.

3. Industrial scale adoption

Efforts are being made to standardize natural dyeing processes for reproducibility and scalability in textile industries. Eco-labels and certifications are developed to increase consumer expectation in naturally dyed products (Negi, 2025) ^[25]. These eco-labels help consumers identify eco-friendly products. Standards like GOTS (Global Organic Textile Standard) ensure that natural dyes are free of harmful substances and sustainably sourced.

4. Global market expansion

Growing demand for eco-fashion, organic cosmetics, and sustainable packaging is propulsive research and investment. Natural dyes are progressively established as premium, value-added products in international trade (Negi, 2025) ^[25].

5. Bioengineered dyes and biomordants

Advancements in biotechnology enable the cultivation of colour-producing microorganisms such as algae, fungi, and bacteria. Furthermore, fermentation extraction methods are being investigated to generate natural pigments such as indigo and anthocyanins without harming ecosystems (da Silva Jr, *et al.*, 2021) ^[7].

6. Innovations in mordants

Development of bio-based mordants from plant tannins and organic acids, replacing heavy metals such as chromium and alum. Tannins are natural mordant agents, widely distributed in almost all part of plant such as roots, bark, stems, leaves, and fruits. These mordants ensure colourfastness without harming ecosystems.

7. Nanotechnology applications in natural dyeing

Nanotechnology is revolutionizing both the extraction and application processes. This technique improves dye efficiency, colour intensity, and sustainability of textile colouration based on natural dye. Nanoparticles can be applied to encapsulate dye molecules, safeguarding them from degradation and enabling controlled release at the time of dyeing. This results in higher uptake of dye by fibers, providing more vibrant and longer-lasting colours. Nanotechnology also facilitate consistent and even distribution of natural dye across textile substrate. Nanoparticles can be tailored to improve dye surface adherence, penetration, and fixation, leading to enhanced colourfastness and minimized dye wastage (Ludin *et al.*, 2014) ^[19].

Conclusion

Natural dyes provide sustainable, biodegradable, and culturally significant alternatives to synthetic colourants, addressing environmental and health implications in textile production. Advancement in extraction techniques, mordanting processes, and biotechnology have Heightened their applicability, whilst innovations including plasma, ultrasonic, and microwave technologies increase dyeing efficiency and scalability. In spite of challenges of cost and limited raw material availability, synthesizing natural dyes into circular economy models and industrial practices indicates their strong potential for eco-friendly fashion and textiles. Continued research, technological development and standardization will be necessary to ensure their role in global sustainable industries.

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