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DYES: NATURAL Vs SYNTHETIC- A REVIEW

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ABSTRACT

Dyes are coloured compounds that impart lasting colour to substrates through absorption of specific wavelengths of light, primarily in the visible region. Natural dyes have been used since ancient times for colouring and printing textiles. However, rapid advancements in the field of chemistry have led to the development of a vast array of synthetic dyes, offering vibrant colours with superior fastness properties. This review paper delves into the fascinating world of dyes, providing a brief overview of their historical development, classification and sources, with a specific emphasis on the comparison between natural and synthetic dyes. The paper also explores the chemical structures and functional groups of various dyes, including chromophores and auxochromes. Furthermore, it discusses the health and environmental hazards associated with synthetic dyes, underlining the importance of sustainable alternatives and effective remediation strategies.

KEYWORDS: Dyes, Chromophores, Auxochromes, Electromagnetic radiations, Electronic transitions, Chlorophyll

Historical development from natural to synthetic dyes

Dyes are defined as the coloured substances that, when applied to a material, impart a permanent colour resistant to the effects of light, heat and water. Dyes today are indispensable across various industries including textiles, leather, food, plastics and cosmetics (Carvalho and Santos, 2015). Dyeing is a complex and specialized science that requires an understanding of the interaction between electromagnetic radiation and dye molecule, particularly the absorption and emission of specific wavelengths. Modern dye theories are rooted in quantum chemistry. Valanced bond theory (VBT) and molecular orbital theory (MOT) explain the optical behavior of dye molecules through:

- Quantization of energy and electronic transitions.
- Selective absorption in the visible region.
- Conjugation and resonance (Lewis and Lewis, 2000), which lower the energy gap for excitation.
- Presence of chromophore and auxochromes that modulates absorption intensity and wavelength.
- Dipole moment of a molecule, which influences its interaction with electromagnetic radiation.

The practice of dyeing textiles spans thousands of years and reflects the interplay of cultural, technological and artistic advancements across civilizations. As documented by Koren (1993), the art of dyeing developed independently in multiple geographic regions. The earliest recorded use of dyestuffs in China dates back to around 2600 BC (Krizova, 2015), while by 3000 BC, dyeing was already a well-established art in Egypt (Kareem, 2012), Mexico and Peru. Ancient Egyptian textile industries, among the oldest known, naturally led to the experimentation with and application of pigments to fabrics (Barber, 1991). Archaeological evidence from Egyptian tombs reveals the use of natural dyes as early as several millennia BC (Robertson, 1973). Throughout antiquity, dyers sourced a wide array of natural colorants from plant, animal and mineral origins to colour fabrics (Weigle, 1974). It is estimated that nearly one thousand distinct natural dyes were used globally by early civilizations.

During the early Bronze Age, dyeing practices became more refined, with artisans discovering various dye sources to expand the available colour palette (McLaren, 1983). In the late Bronze age alizarin, purpurin and indigo were used in textile industry in Chinese Yanghai (Kramell *et al.*, 2014). By the 16th century, countries including France, Holland and Germany began large scale cultivation of dye plants, marking a shift towards commercial production. In sub-Saharan Africa, particularly Nigeria, the use of plant-based dyes was closely intertwined with cultural identity and regional trade (Okoro, 2011). Likewise, the Turkish DOBAG project exemplified the revival of traditional dyeing methods, utilizing madder root and insect-based dyes to produce naturally dyed carpets (Turan, 2018). In the Americas and Scotland, natural dyes sourced from native flora and fauna played a significant role in textile coloration (Phipps *et al.*, 2003). Fruits of privet were commonly used in Scotland to dye wool (Grierson, 1984). In Africa, plant and mineral based dyes remain essential in textile production (Adeyemi, 2020). Egyptians also relied extensively on natural dyes, with applications

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extending beyond utility to ceremonial and symbolic purposes. Today, natural dyes are still used in niche markets, including textiles, food and artisanal crafts (Cardon, 2007), valued for their environmental compatibility and aesthetic appeal.

The 19th century marked a paradigm shift with the emergence of synthetic dyes (Levchik, 2011), fundamentally transforming the textile industry. Until this point, natural were the predominant means of fabric colouration. However, with the advent of synthetic organic chemistry, the textile industry underwent a profound transformation. The synthesis of mauveine in 1856 by William H. Perkin, originally during an attempt to synthesize quinine, heralded the birth of synthetic dye chemistry (Lewis, 2011). This was soon followed by the development of fuchsine by Graebe and Liebermann in 1858 (Wainerdi, 2012). Other early synthetic dyes include picric acid, synthesized by Woulfe and rosolic acid by Runge.

Synthetic dyes rapidly displaced their natural counterparts across multiple industries including textiles, paper, leather, plastics and food (Bhattacharjee *et al.*, 2017). Their vibrant hues, enhanced fastness properties, cost efficiency and ease of mass production contributed to their widespread adoption. These advancements not only accelerated industrial manufacturing processes but also democratized access to colourful textiles and materials (Leonnard *et al.*, 2023). Moreover, synthetic dyes enabled innovations in printing, visual arts and fashion, thereby playing a crucial role in modern culture and economic development (Moring and Ott, 2015). Today, synthetic dyes dominate the global market, comprising over 99% of all dyes used worldwide.

Classification of dyes

Dyes are classified in several ways, often based on their sources, chemical structure and method of application (Kombey *et al.*, 2023). Each dye class has a characteristic chromophore and application profile tailored for fiber types and end-uses. Here's a classification tree is depicted in Figure 1 encompassing these categories.

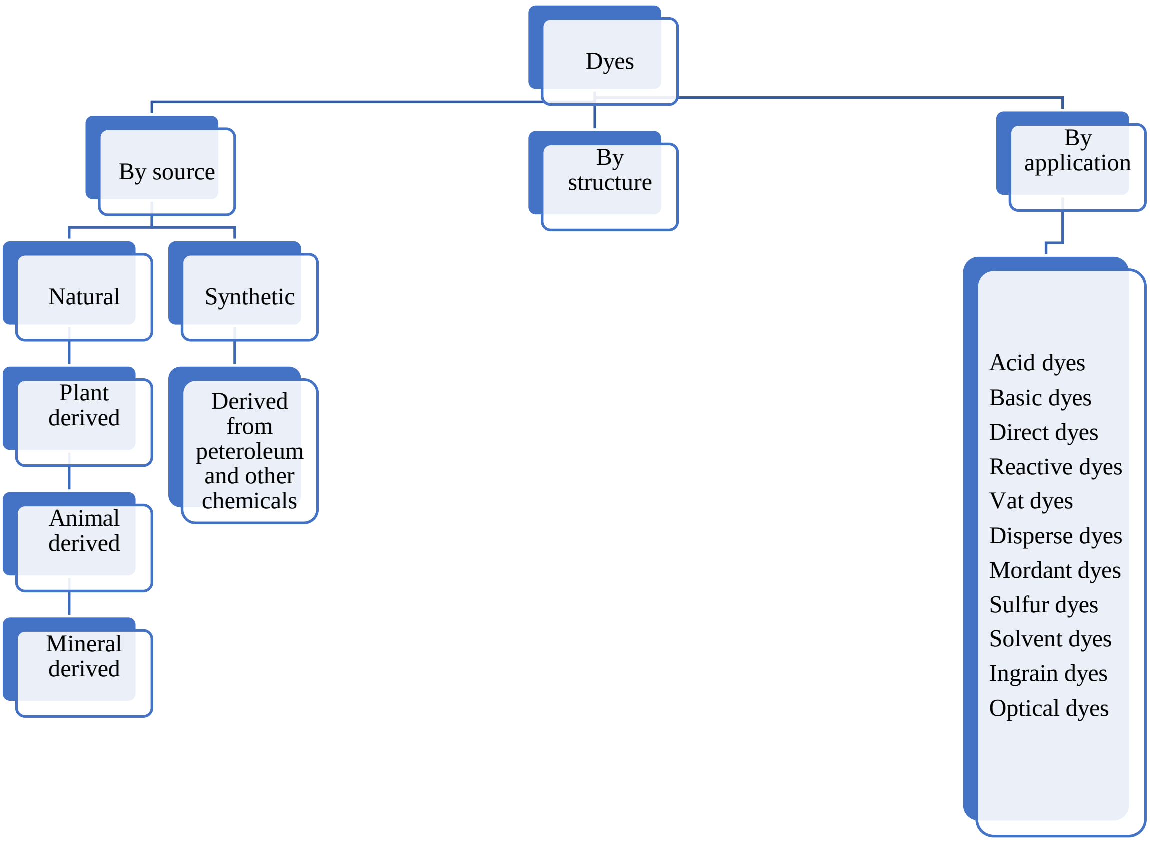


Figure 1: Classification of dyes

Classification of dyes based on their origin

Dyes can be classified by their origin as either natural or synthetic. Natural dyes are derived from plants, animals or minerals, while synthetic dyes are synthesized through chemical synthesis.

Natural dyes

Natural dyes, discovered through the ingenuity and persistence of early civilizations, have been used since antiquity by cultures across the world to colour textiles, food and various materials. These dyes are highly valued today for their ecofriendly characteristics, including non-toxicity, biodegradability and minimal environmental impact (Kadolph, 2008). A wide array of natural sources as, plants, animals and minerals has been identified, for the extraction of natural dyes and pigments.

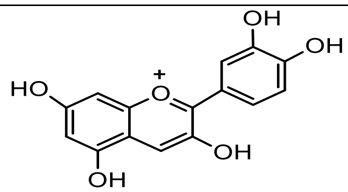
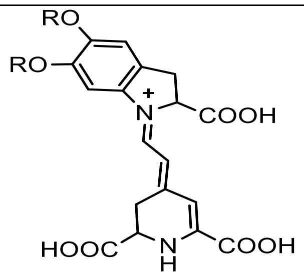
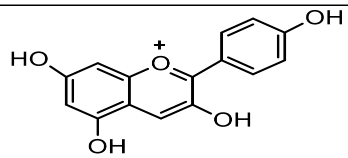
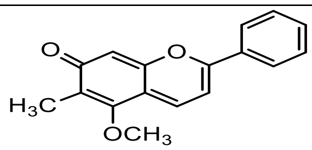
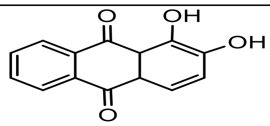
Plant-based dyes have a particularly rich history, being widely used in traditional textile practices, crafts and artworks. These dyes are extracted from diverse parts of plants such as roots, leaves, stems, flowers, barks and seeds. Examples include blue dye from indigo (Indigofera tinctoria) and woad (Isatis tinctoria), yellow dye from turmeric (Curcuma longa), orange dye from madder (Rubia tinctorum), brown dye from kola nut (Cola acuminata). These dyes offer a broad palette of hues, and their widespread availability has made them essential to indigenous dyeing traditions. Some of the plants and their parts that have been explored for dyes are summarized in Table 1 and the chemical structure of their colorant is depicted in Table 2.

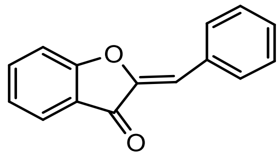
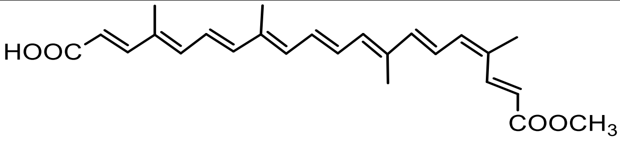
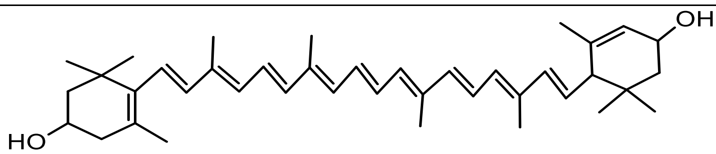
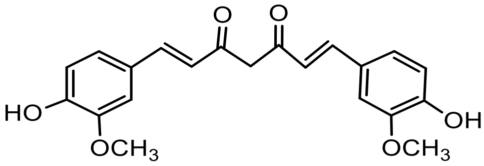
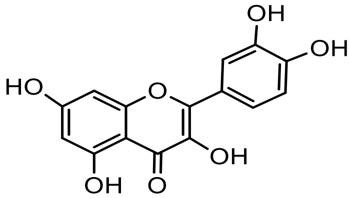
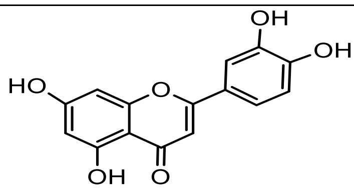
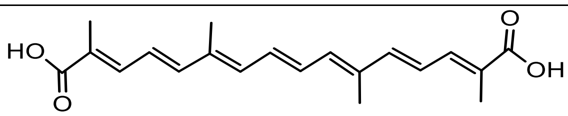
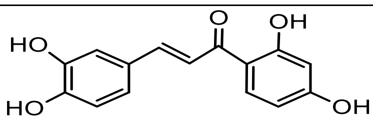
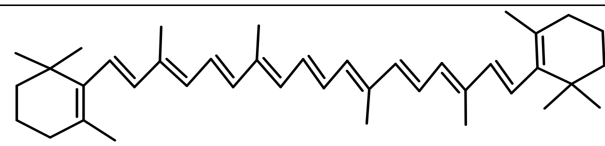
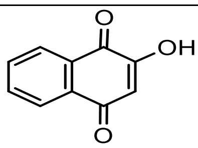
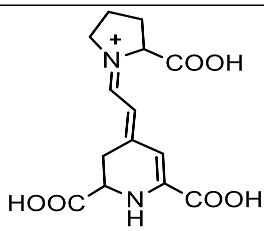
Table 1: List of plant derived natural dyes

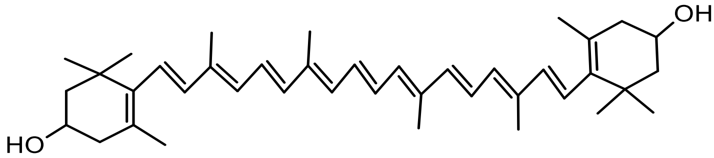
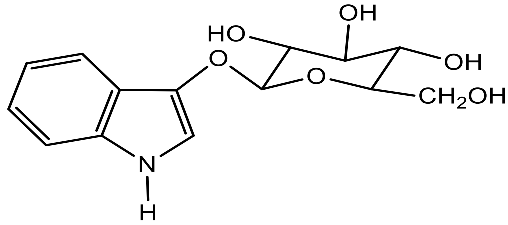
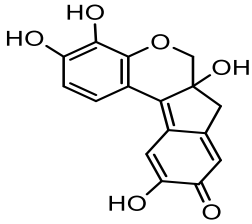
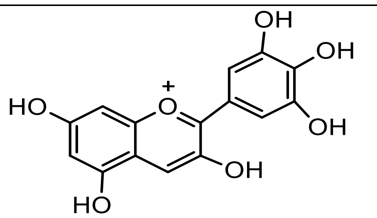
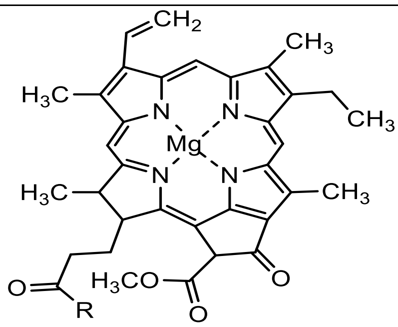
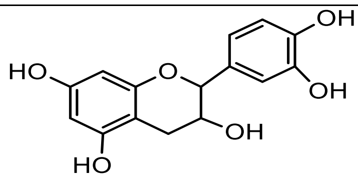
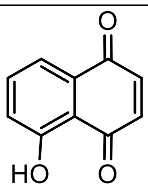
Colour obtained	Plant	Botanical name	Origin	Natural colourant	Class	Ref
Red	Roselle	*Hibiscus sabdariffa*	Calyces	Cyanidin	Anthocyanin	Mansur *et al.*, 2014
	Paper flower	*Bougainvillea glabra*	Bracts	Betacyanins	Betalain	Shivani *et al.*, 2020
	Barberton daisy	*Gerbera jamesonii*	Flower	Cyanidin	Anthocyanin	Shivaji *et al.*, 2014
	Indian fig opuntia	*Opuntia ficus indica*	Fruit	Betacyanins	Betalain	Ganesan and Karthik, 2017
	Rose	*Rosa sp*	Flower	Cyanidin	Anthocyanin	Patil *et al.*, 2016
	Sword lily	*Gladiolus palustris*	Flower	Pelargonidin	Anthocyanin	Ijaz, 2020
	Tropical dogwood	*Mussaenda erythrophylla*	Flower	Pelargonidin	Anthocyanin	Manicketh *et al.*, 2022
	Rosary pea	*Abrus precatorius*	Seed	Cyanidin	Anthocyanin	Vetter, 2001
	Dragon's blood tree	*Dracaena cinnabari*	Resin	Dracorhodin	Anthocyanin	Melo *et al.*, 2007
Orange	Madder	*Rubia tinctorum*	Roots	Alizarin	Anthraquinone	Tylor, 1990
	Snapdragon	*Antirrhinum majus*	Flower	Aurone	Flavonoid	Gaurav, 2022
	Annatto	*Bixa orellana*	Seeds	Bixin	Carotenoid	Perdomo *et al.*, 2015
Yellow	Pot marigold	*Calendula officinalis*	Dried petals	Lutein	Carotenoid	Akinola and Adeyemi, 2019
	Turmeric	*Curcuma longa*	Rhizome	Curcumin	Polyphenols	Gupta *et al.*, 2013
	Champak	*Magnolia champaca*	Flower	Quercetin	Flavonoids	Rane and Patil, 2016
	Weld	*Reseda luteola*	Flower	Luteolin	Flavonoids	Andry and Prunace, 1995
	Saffron	*Crocus sativus*	Flower	Crocetin	Carotenoid	Mills and White, 1987
	Marigold	*Tagetes reecta*	Flower	Lutein	Carotenoid	Farooq *et al.*, 2013
	Palash	*Butea monosperma*	Flower	Butein	Flavonoid	Daberao *et al.*, 2016
	Frangipani	*Plumeria rubra*	Flower	Quercetin	Flavonoid	Swamy *et al.*, 2016
	Wild sage	*Lantana camara*	Flower	β-Carotene	Carotenoid	Datta *et al.*, 2023
	Parijat	*Nyctanthes arbortristis*	Flower	Crocetin	Carotenoid	Adeel *et al.*, 2022
	Annatto	*Bixa orellana*	Seeds	Bixin	Carotenoid	Selvi *et al.*, 2013
	Henna	*Lawsonia inermis*	Leaves	Lawsone	Quinonoid	Kanniappan, 2015
	Nasturtium	*Tropaeolum majus*	Flower	Lutein	Carotenoid	Singh *et al.*, 2021
	Indian fig opuntia	*Opuntia ficus indica*	Fruit	Indicaxanthin	Betalain	Butera *et al.*, 2002
	Yellow bells	*Tecoma stans*	Flower	Zeaxanthin	Carotenoid	Chandra *et al.*, 2012
	Yellow Delphinium	*Delphinium zalil*	Flower	Quercetin	Flavonoids	Kiumarsi *et al.*, 2017

Blue	Indigo	*Indigofera tinctoria*	Leaves	Indican	Glycosides	Adeyanju *et al.*, 2011
	Logwood	*Haematoxylum campechianum*	Heartwood	Hematein	Haematoxylin	Wickens, 1983
	Woad	*Isatis tinctoria*	Leaves	Indican	Glycosides	Cannon and Cannon, 1994
	Butterfly pea	*Clitoria ternatea*	Flower	Delphinidin	Anthocyanin	Ashraf *et al.*, 2024
Green	Banana	*Musa sapientum*	Leaves	Chlorophyll	Porphyrins	Adeoye and Oyedeji, 2018
	Screwpine	*Pandanus amaryllifolius*	Leaves	Chlorophyll	Porphyrins	Rosli *et al.*, 2021
Brown	Cockscomb	*Celosia cristata*	Flower	Betacyanins	Betalain	Shanker and Vankar, 2005
	Kola nut	*Cola acuminata*	Husks	Catechin	Tannin	Okwu and Omodamiro, 2014
	Black walnut	*Juglans nigra*	Hulls	Juglone	Naphthoquinone	Chemchame *et al.*, 2020
	Cutch	*Acacia catechu*	Heartwood	Catechin	Tannin	Dalby, 1989
Purple	Globe Amaranth	*Gomphrena globosa*	Flower	Betacyanins	Betalain	Roriz *et al.*, 2020
	Jungle geranium	*Ixora coccinea*	Flower	Cyanidin	Anthocyanin	Ghurde *et al.*, 2016
	Yam	*Dioscorea rotundata*	Flesh	Cyanidin	Anthocyanin	Obirikorang *et al.*, 2014
Violet	Burans	*Rhododendron arboreum*	Flower	Cyanidin	Anthocyanin	Kim *et al.*, 2013
Pink	China Aster	*Callistephus chinensis*	Flower	Quercetin	Flavonoid	Nair *et al.*, 2014
Lavender	Water hyacinth	*Eichhornia crassipes*	Flower	Delphinidin	Anthocyanin	Gopika *et al.*, 2018

Table 2: Chemical structure of colorants of plant derived dyes

Colorant	Chemical structure
Cyanidin	
Betacyanins	
Pelargonidin	
Dracorhodin	
Alizarin	

Aurone	
Bixin	
Lutein	
Curcumin	
Quercetin	
Luteolin	
Crocetin	
Butein	
β-Carotene	
Lawsone	
Indicaxanthin	

Zeaxanthin	
Indican	
Hematein	
Delphinidin	
Chlorophyll	
Catechin	
Juglone	

Animal / insect / microbial-based dyes, through less commonly used today, have historically held cultural and economic significance. Derived from components such as shells, bones, scales and secretions, these dyes offer unique shades ranging from earthy tones to vibrant purples and reds. Notable examples include cochineal (extracted from Dactylopius coccus), known for its brilliant crimson colour; Tyrian purple (from marine mollusks); sepia (from squid ink) and bone black (from charred animal bones). These dyes are once prized commodities in trade and played key roles in rituals and textile traditions. Representative examples of animal / insect / microbial derived dyes are summarized in Table 3.

Table 3: List of animal derived natural dyes

Dye	Source	Zoological name	Colour	Colorant	Class	Ref
Cochineal	Insect	*Dactylopius coccus*	Red	Carminic acid	Anthraquinone	Brown, 2018
Lac dye	Insect	*Coccus laccae*	Red	Laccaic acid	Polyketide	Goffer, 1980
Orchil dye	Lichen	*Lichen roccella*	Purple and red	Orcein	Phenoxazone	Geijer, 1982
Kermes	Insect	*Coccus ilicis*	Red	Kermesic acid	Anthraquinone	Mustafa *et al.*, 2020
Tyrian purple	Sea snails	*Murex trunculus*	Purple	6,6′-dibromoindigo	Indigoids	Taylor, 2017
Sepia dye	Cuttlefish	*Sepia officinalis*	Brown	Eumelanin	Melanin	Jones, 2019
Shellfish dye	Mollusks	*Hexaplex trunculus*	Purple	6,6′-dibromoindigo	Indigoids	Smith, 2015
Guanine crystals	Fish	*Clupea harengus*	Silvery pigment	Guanine	Purines	Green, 2020
Bone black dye	Cattle bones	*Bos taurus*	Black	Carbon black	Carbon and calcium hydroxyapatite	Nwankwo *et al.*, 2018
Squid ink	Squid	*Loligo vulgaris*	Black	Melanoprotein	Melanin	Johnson, 2021

Mineral-based dyes, also known as inorganic and mineral pigments, are derived from naturally occurring minerals. These pigments are renowned for their exceptional stability and resistance to fading, heat and chemical degradation. Unlike organic dyes, mineral pigments retain their vibrancy and integrity over time, making them ideal for applications requiring long-term durability. Historically, they have been used in mural paintings, ceramics, cosmetics and scared art. Prominent examples include red ochre (iron oxide), lapis lazuli (ultramarine blue). Their role in art conservation and archaeological studies is also significant; for example, the analysis of mineral pigments in cave art has provided insights into early human civilization, resource use and cultural symbolism. Select examples of mineral derived dyes are summarized in Table 4.

Table 4: List of mineral derived natural dyes

Mineral / Pigment	Occurrence	Chemical composition	Colour obtained	Ref
Ochre	Iron oxide rich clay and sand	Iron oxide	Yellow, brown, red	Black, 2017
Malachite	Mined in the Urals (Russia), US etc	Copper carbonate + copper hydroxide	Green	Gettens and Fitzhugh, 1993
Pyrolusite	Oxidising sedimentary environment like lakes	Manganese dioxide	Black	Chalmin *et al.*, 2006
Cinnabar	Hydrothermal veins, hot springs and volcanic areas	Mercury sulfide	Red	Kvascev *et al.*, 2012
Azurite	Oxidized zones of copper deposits	Copper ore	Deep blue	Gettens and Fitzhugh, 1993
Lapis lazuli	Sar-e-Sang deposit in Kotcha valley, Afghanistan	Silicate + Calcite + Pyrite	Blue	Green, 2005
Crocoite	Oxidized zones of lead deposites	Lead chromate	Red	Hans, 2006
Eskolaite	Chromium rich skarns, metaquartzites and chlorite veins	Chromium oxide	Green	Gerd *et al.*, 2005
Prussian blue	Synthesized piment	Iron cyanide	Blue	Berrie, 1997
Realgar	Hydrothermal veins associated with volcanic activity and hot springs	Arsenic sulfide	Red	FitzHugh, 1997

Synthetic dyes

Synthetic dyes offer a vast spectrum of colours and have significantly supplanted natural dyes, primarily due to their cost effectiveness, ease of production and versatility. These dyes are highly attractive from both industrial and artistic perspectives, as they provide superior colour fastness and more intense hues compared to their natural counterparts. Their robust application potential has led to revolutionary developments in areas such as halochromic textiles, dye-sensitized solar cells and enhanced liquid crystal displays. Moreover, synthetic dyes play a crucial role in the development of multifunctional textiles that go beyond aesthetic appeal. Today's dye-infused fabrics can exhibit antibacterial properties, UV protection, self-cleaning features and much more. A notable contribution by various researchers in this domain is summarized in table 5.

Table 5: List of synthetic dyes and their uses

Synthetic dye	Use	Reference
Azo dyes based on benzophenone	Dyeing wool	Bait *et al.*, 2020
Azo dyes based on dihydroxy naphthoate	Dyeing acrylic material	Ramugade *et al.*, 2019
Azo dyes based on coumarin	Dyeing nylon fabrics	Ayare *et al.*, 2019
Azo dyes containing urethane	Dyeing polyamide material	Fang *et al.*, 2020
Acid dye	Dyeing cotton fabrics	Rehan *et al.*, 2020
Azo disperse dyes	Dyeing wool	Li *et al.*, 2018
D-π-A dyes	Dye-Sensitized Solar Cells application	Wu *et al.*, 2014
Triazatetrabenzcorrole dyes	LCD colorant	Choi *et al.*, 2013
Perylene diimide dyes	Development of black matrix	Yuk *et al.*, 2015
Perylene diimide dyes bearing thiophene	Sensor for Hg^{2+}	Malkondu and Erdemir, 2015
Benzoquinolinium dyes	Detection of G-quadruplex DNA	Wang *et al.*, 2019
Tartrazine	Used in food and cosmetic industries	Garg *et al.*, 2019
Allura red	Used in food and cosmetic industries	Deng *et al.*, 2021
Brilliant blue	Used in pharmaceutical industries	Wang *et al.*, 2018
Sunset yellow	Used in food and cosmetic industries	Rovina *et al.*, 2016
Indigo carmine	Used in food and pharmaceutical industries	Durrani *et al.*, 2021
Erythrosine	Used in food and cosmetic industries	Ramakrishnan *et al.*, 2011
Fast green	Used in food and cosmetic industries	Hooft, 2002

Classification of dyes based on chemical structure

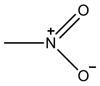
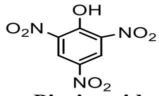
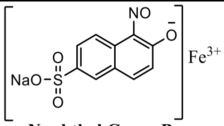
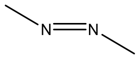
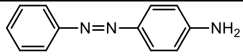
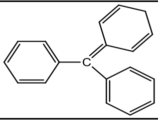
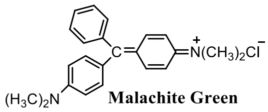
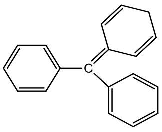
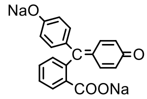
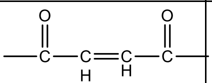
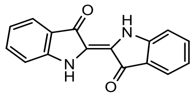
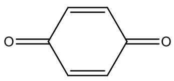
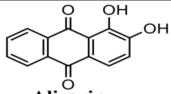
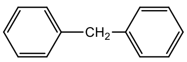
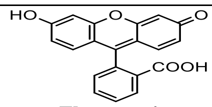
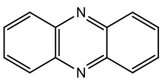
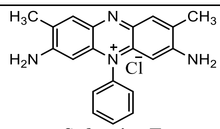
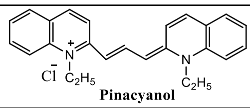
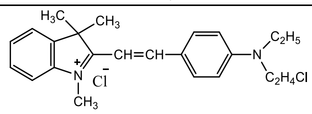
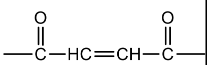
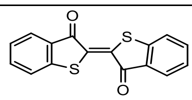
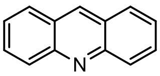
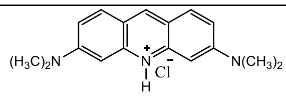
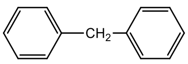
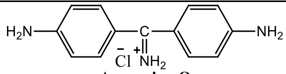
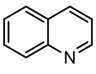
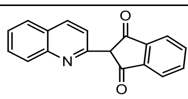
The classification of dyes based on their chemical structure is one of the most scientifically robust and widely accepted approaches. This approach classifies dyes based on the presence of specific chromophores and auxochromes (Table 6), which are central to their colour producing properties.

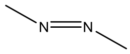
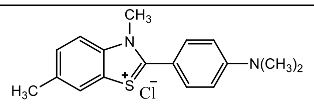
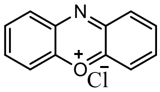
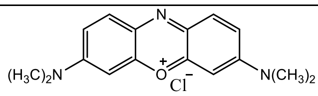
Chromophores are the core structural units responsible for light absorption. These groups typically possess conjugated π-electron systems that enable electronic transitions upon exposure to light. By absorbing specific wavelengths, chromophore reflect complementary colours, thereby giving dyes their characteristic hues. Based on the type of chromophores, dyes can be classified into several major categories.

Auxochromes are functional groups that, when attached to a chromophore, enhance the dye's colour intensity and affinity for substrates. They can alter the shade and depth of colour by causing shifts in the chromophore's absorption spectrum.

This classification framework allows for the rational design and selection of dyes for specific applications such as textiles, biological staining, food colouring and photonic devices. Furthermore, understanding the relationship between structure and function is essential for the development of novel dyes with improved performance, environmental compatibility and application-specific properties.

Table 6: Classification of dyes on the basis of characteristic structural units

Class	Chromophore	Auxochrome	Example
Nitro dyes		-OH	 **Picric acid**
Nitroso dyes	O═N──	-OH	 **Naphthol Green B**
Azo Dyes		$-NH_2$	 **Aniline Yellow**
Triphenylmethane dyes		$-NH_2$	 **Malachite Green**
Phthalein dyes		-OH	 **Na-salt of phenolphthalein**
Indigo dyes		$-NH_2$, -OH	 **Indigo**
Anthraquinone dyes		-OH	 **Alizarin**
Xanthene dyes		-OH	 **Fluorescein**
Azine dyes		$-NH_2$	 **Safranine T**
Cyanine dyes	═CH─CH═CH──	$-NH_2$	 **Pinacyanol**
Polymethine dyes	═CH─CH═CH──	$-NH_2$	 **Astrazone Pink FG**
Indigoid dyes		Sulphur atoms	 **Thio Indigo**
Acridine dyes		$-NH_2$	 **Acridine Orange R**
Diphenylmethane dyes		$-NH_2$	 **Auramine O**
Quinoline dyes		-OH and N atom within the quinoline ring	 **Quinoline Yellow**

Thiazole dyes		$-NH_2$	 **Methylene Yellow N**
Oxazine dyes		$-NH_2$	 **Capri blue GN**

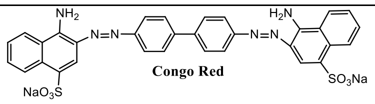
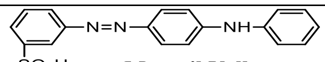
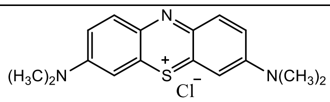
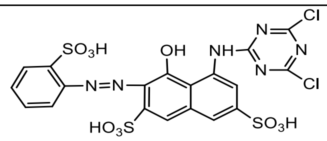
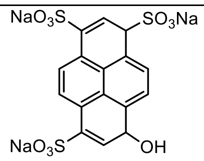
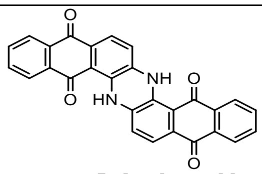
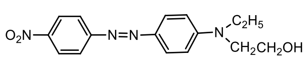
Classification of dyes based on method of application

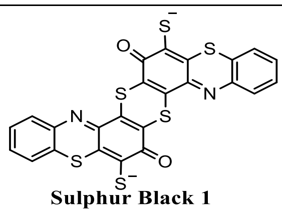
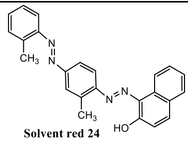
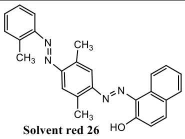
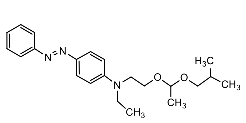
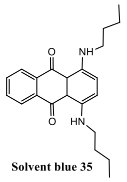
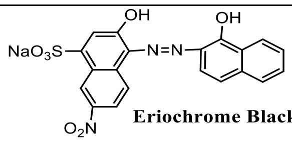
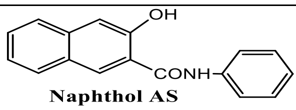
The application method of a dye is determined primarily by the chemical structure of the dye, type of fiber and physical properties such as solubility, affinity and fastness characteristics. These variables strongly influence the interaction between the dye and the substrate during dyeing or printing process.

Unlike chemical classification, which groups dyes based on chromophoric systems, the application-based classification takes into account how the dye is transferred and fixed to the fiber. Notably, dyes with similar molecular structures may fall under different application classes if they require different processes for fiber attachment.

In industrial practice, choosing the correct dye class for a given fiber type is essential to ensure optical colour yield, fastness and process efficiency. Some dyes are directly applied in their final form (e.g., direct dyes), while others undergo chemical transformations either before or during the dyeing process (e.g., vat dyes, ingrain dyes). Table 7 provides an overview of the primary dye classes based on the mode of application, along with their examples, suitable fibre types and typical application method.

Table 7: Classification of dyes based on method of application

Type	Example	Application method	Suitable fibers
Direct dyes	 **Congo Red**	Applied from aqueous solution with electrolyte	Cotton, viscose, linen
Acid dyes	 **Metanil Yellow**	Applied from acidic dye bath, dye-fibre interaction via ionic bonds	Wool, silk, nylon
Basic dye	 **Methylene blue**	Applied from neutral or slightly acidic bath, ionic interaction with acidic groups in fibre	Acrylic, paper, polyester
Reactive dye	 **Procion Brilliant Red M-2B**	Form covalent bonds with fibre, require alkaline pH and heat	Cotton, wool, silk, nylon
Optical dye	 **Solvent Green 7**	Soluble in water and other solvents like glacial acetic acid and 30% hydrochloric acid	Paper, wood stains and transparent lacquers
Vat dye	 **Indanthrone blue**	Insoluble in water, reduced to soluble leuco form before application and then oxidized	Cellulose fibres
Disperse dye	 **Celliton Scarlet B**	Dispersed in water and adsorbed by hydrophobic fibres at high temperature	Polyester, cellulose acetate, nylon

Sulphur dye	 Sulphur Black 1	Insoluble dyes made soluble via reduction, reoxidized on fibre	Cotton, viscose
Solvent dyes	 Solvent red 24  Solvent red 26  Solvent yellow 124  Solvent blue 35	Applied using organic solvents instead of water	Plastics, resins, waxes, leather
Mordant dye	 Eriochrome Black T	Require pre or post treatment with mordant (e.g. metal salt) to fix the dye	Wool, silk, cotton
Ingrain dye	 Naphthol AS (Azoic Coupler)	Components applied separately, dye forms within the fibre by diazotization and coupling	Cotton, viscose

Challenges of natural and synthetic dyes

Natural dyes

Natural dyes, derived from plant, animal and mineral sources, have been historically used in textile and material colouration. However, their industrial applicability remains limited due to several intrinsic constraints. The colour spectrum of natural dyes is inherently narrow, primarily encompassing hues of red, yellow, blue and brown. Secondary colours often require the use of mordants, chemical agents that assist in the fixation of dyes to substrates. From a chemical standpoint, natural dyes are typically complex mixtures of multiple compounds, which complicates purification, standardization and structural characterization. Additionally, the extraction and dyeing processes are labour intensive, yield low concentrations of usable pigment and require considerable expertise. A significant limitation is the poor fastness properties of most natural dyes; they tend to fade when exposed to light and exhibit low resistance to washing and perspiration. These drawbacks collectively hinder their suitability for modern large scale textile production and commercialization.

Synthetic dyes

In contrast, synthetic dyes have revolutionized the dyeing industry by offering a broad spectrum of vivid and stable colours, high reproducibility and cost-effective mass production. Despite these advantages, the use of synthetic dyes is associated with substantial environmental and health risks.

Occupational exposure to certain classes of synthetic dyes; particularly reactive, vat and disperse dyes has been linked to adverse health effects. Reactive dyes are known to cause respiratory issues, including occupational asthma, while vat and disperse dyes can act as skin sensitizers, leading to allergic contact dermatitis. Moreover, textile effluents often contain unbound dyes and toxic heavy metals such as chromium (Cr), arsenic (As), copper (Cu) and zinc (Zn), which can enter water bodies and soils, causing bioaccumulation and toxicity in aquatic and terrestrial ecosystems.

Azo dyes, widely used for cotton fibers, can degrade into aromatic amines, several of which are classified as potential carcinogens. Compounds such as 1,4-diaminobenzene (p-phenylenediamine) have been associated with systematic toxicity, including symptoms such as hypertension, vertigo, exophthalmos and respiratory distress. Notably, a study conducted in 1992 revealed that certain aromatic amines markedly increase the risk of bladder cancer in exposed individuals.

From an ecological perspective, the persistence and non-biodegradability of synthetic dyes contribute to long-term environmental degradation. Their presence in effluents disrupts the natural balance of aquatic systems and impairs soil fertility, adversely affecting microbial populations essential for sustainable agriculture. A comparative study between natural and synthetic dyes is displayed in Table 8.

Table 8: Dyes: Natural Vs synthetic

Parameter	Natural Dye	Synthetic Dye
Source	Derived from natural sources as plants, animals and minerals.	Derivative of natural dyes
Expenditure	Natural dye materials are scarce and expensive.	Generally available at low cost.
Biodegradability	Biodegradable and decomposes easily.	Non-biodegradable and decomposition lead to human health and environmental hazards.
Yield	Yield is about to 45-70%.	Average yield is about 80-90%.
Impact on human health	Better for human health	Contains carcinogenic components and harmful chemicals, potentially leading to skin and respiratory allergies.
Impact on environment	Ecofriendly	Causes harm to the environment and surrounding communities.
Sustainability	More viable option due to their less toxic nature.	Hazardous to environment and human health due to their higher toxicity.

CONCLUSION

Natural dyes offer a viable and greener alternative to synthetic dyes. In contrast, synthetic have gained dominance due to their vast colour gamut, superior fastness properties, cost-effectiveness and ease of industrial-scale production. This comprehensive review highlights the enduring relevance and renewed interest in natural dyes, particularly in light of growing concerns over the environmental and health impacts associated with synthetic alternatives. Among the various sources, flower crops have emerged as a promising category due to their widespread availability, vibrant colour range and natural abundance. Their integration into dye production aligns well with the global movement towards sustainable and ecofriendly practices.

Considering the current state of scientific advancement, natural dyes remain more suited for small-scale and cottage industry applications. While they may not yet replace synthetic dyes in high-volume industrial usage, they can effectively complement them in niche, eco-conscious markets. With continued research and technological refinement, natural dyes hold promise as part of a more sustainable and diversified dyeing future.

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