

NATURAL DYEING OF SILK: A REVIEW OF NATURAL SOURCES, DYEING TECHNIQUES, MORDANTS AND SUSTAINABLE APPLICATION

Pavithra, M. R^{1*}, Ashrith S², Arun Kumar M R³

¹Young Professional, Central Silk Board, Bengaluru.

²Post graduate, Department of Sericulture, University of Agricultural Sciences, Bangalore.

³Ph.D. Scholar, Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, University of Agricultural Sciences, Mandya, Karnataka, India.

*Corresponding Author: Pavithra, M. R, pavithradharmapura@gmail.com

ABSTRACT

Natural dyes have attracted renewed scientific and industrial interest as alternatives to synthetic colorants because of concerns about chemical pollution, resource consumption and the sustainability of textile wet processing. Silk, a protein-based natural fibre primarily composed of fibroin and coated by sericin in its raw state, offers considerable potential for natural dyeing owing to its functional groups, surface characteristics, and affinity for several classes of natural pigments. Natural colorants obtained from plants, animals, microorganisms, and agro-industrial residues can produce a wide range of colours on silk. However, their commercial application is often limited by variations in pigment composition, low or inconsistent colour yield, inadequate fastness and the environmental impacts associated with certain mordants and extraction processes. This review examines the major sources of natural dyes suitable for silk, their chemical characteristics, conventional and emerging extraction and dyeing techniques, and the role of metallic and bio-based mordants in colour development and durability. Particular attention is given to recent advances in ultrasound-assisted and microwave-assisted processing, agricultural-waste valorisation, statistical optimisation and multifunctional textile finishing. Recent research demonstrates promising results for plant-derived colourants, lac dye, and waste-derived extracts when appropriate dyeing and mordanting conditions are employed. The review identifies standardisation, reproducibility, fastness improvement, life-cycle assessment, and industrial scalability as important priorities for future research. Integrating renewable dye sources with efficient extraction methods and safer mordanting systems may support the development of more sustainable silk coloration.

KEYWORDS: Natural dyes; silk; fibroin; sericin; bio-mordants; colour fastness; green extraction; sustainable textiles; agro-waste valorisation; eco-friendly dyeing.

1. INTRODUCTION

Textile coloration is an important stage of textile manufacturing, but conventional dyeing and finishing processes can require substantial quantities of water, thermal energy, processing chemicals, and wastewater treatment. These environmental considerations have encouraged researchers to investigate renewable colourants and alternative dyeing technologies. Natural dyes have consequently received renewed attention for their potential applications in clothing, traditional textiles, premium fabrics and environmentally oriented product development. Recent reviews emphasise that progress depends not only on replacing synthetic dyes but also on improving extraction, fibre preparation, mordanting, and overall process efficiency (Pizzicato *et al.*, 2023).

Silk is a valuable protein fibre produced by silkworms and is distinguished by its lustre, softness, drape, tensile characteristics and comfort. Its principal structural component is fibroin, while sericin acts as a protective gum surrounding the fibroin filaments before degumming.

Silk contains amino acid residues and peptide bonds that provide functional groups capable of interacting with suitable dye molecules through hydrogen bonding, electrostatic attraction, van der Waals interactions, and other non-covalent interactions.

Natural dyes may be particularly attractive for silk because the fibre can be coloured under appropriately controlled aqueous and moderately acidic conditions. Nevertheless, dye uptake and final colour depend on the dye's chemical structure, molecular size, solubility, extraction conditions, pH, temperature, fibre preparation, and the use of mordants (Lara *et al.* (2022)).

Recent investigations have explored plant-derived yellow and brown colourants, beetroot pigments, lac-based red colourants, herbal extracts, and combinations of natural dyes for silk coloration. Emerging methods, including ultrasound-assisted extraction, microwave-assisted treatment, and bio-mordanting, offer potential routes to improve colour yield and processing efficiency.

2. Natural sources of dyes for silk

Natural dyes can be classified according to their biological origin, chemical structure and principal colour-producing compounds. Their performance depends on the concentration and stability of the chromophores, their solubility in the dye bath and their interactions with silk.

2.1 Plant-derived dyes

Plants represent one of the most widely investigated sources of natural colourants because their leaves, flowers, roots, bark, fruits, seeds, and agricultural residues contain diverse pigment molecules. Important classes include flavonoids, anthraquinones, carotenoids, tannins, curcuminoids, and betalains.

2.1.1. Turmeric (*Curcuma longa*)

Turmeric contains curcuminoids, particularly curcumin, which produces yellow to golden-yellow shades. Curcumin has a conjugated molecular structure responsible for its colour and is sensitive to pH, light and certain processing conditions. Dye uptake and durability depend on extraction solvent, bath conditions and mordant selection.



However many recent research has investigated ultrasound-assisted turmeric extraction and microwave-assisted dyeing of silk. These approaches may improve pigment extraction and colour yield, although the optimum conditions depend on the process and formulation.

2.1.2. Madder (*Rubia species*)

Madder roots contain anthraquinone pigments, including alizarin and purpurin in relevant species. These colourants can produce red, pink, rust and reddish-brown shades, depending on the mordant and processing conditions. Their interaction with metal ions can substantially alter hue and colour depth.

Madder is a useful reference dye for studying the relationship between pigment structure, metal complex formation and colourfastness. Further comparative studies on silk are needed to establish standardised, low-impact dyeing conditions.



2.1.3. Pomegranate (*Punicagranatum*)

Pomegranate peel is rich in hydrolysable tannins and other polyphenolic compounds. Its extracts can produce yellow, beige, olive and brown shades, with the final colour depending on the mordant and extraction conditions.

Pomegranate peel is particularly interesting as an agricultural by-product and as a potential source of tannin-rich bio-mordant material. However, its use as a dye, a mordant or both should be distinguished experimentally because these functions are not necessarily equivalent.



2.1.4. Beetroot (*Beta vulgaris*)

Beetroot contains betalain pigments, including red-violet betacyanins. These pigments are attractive for developing red and purple shades but can be sensitive to temperature, pH, oxygen, and light.

Mia et al. (2025) investigated ultrasound-assisted extraction of beetroot pigments for silk dyeing and compared orange-peel extract, lemon-peel extract, tannic acid, ferrous sulfate, and alum as mordanting agents. The study provides a useful example of combining extraction technology with a comparison of different mordant systems.



2.1.5. Marigold (*Tagetes erecta*)

Marigold petals contain carotenoid pigments that can produce yellow and orange shades. A 2026 study investigated marigold dyeing of Eri silk using *Emblica officinalis* as a plant-based bio-mordant. The reported results support further investigation of natural mordants for specialty silk fibres.



2.1.6. Onion peel (*Allium cepa*)

Onion skins contain flavonoids, particularly quercetin and related compounds, and can yield yellow, orange-brown and brown shades. Their availability as a kitchen and agricultural residue makes them promising for small-scale natural dyeing.

Research on onion peel for silk should evaluate extract composition, dye exhaustion, mordant requirements, fastness, and the influence of seasonal variation in raw materials.

Other plant sources of interest include walnut husks, henna (*Lawsonia inermis*), *Artemisia argyi*, *Cassia fistula*, *Sesbania aculeata*, *Terminalia catappa* and *Bombax ceiba*. Recent silk-focused studies have examined several of these species and their potential use with bio-mordants or improved extraction methods.

2.2. Animal-derived dyes

Few insects and molluscs contain extractable colourants in their bodies. Colourants carminic acid, kermesic acid and laccaic acid originate from the dried bodies of insects - cochineal, kermes and lac respectively (Yusuf *et al.*, 2017a). Cochineal (*Dactylopius coccus*) is a scale insect, and the bodies of female cochineals and their eggs contain carminic acid (C.I. Natural Red 4), which has found applications in food colouration, drug and textile dyeing. This colourant produces a variety of shades of pink, crimson red, scarlet red, and blue onto natural fibres when used with different mordants (Adeel *et al.*, 2018). Kermes (*Kermes vermilio*) is another scale insect, and like cochineal, the bodies of female kermes and their eggs contain colouring substances. This insect is the source of a yellowish-red dye kermesic acid (C.I. Natural Red 3). Kermes powders were used for textile dyeing in ancient England, France, Spain, Turkey, and Scotland. Another red dye C.I. Natural Red 25, is obtained from the resinous secretion of different species of lac insects – *Laccifer lacca* and *Kerria lacca*.

2.2.1. Lac dye

Lac dye is obtained from lac insects, traditionally associated with *Kerria lacca*. Its red colour is mainly associated with laccaic acid pigments. Depending on extraction and mordanting conditions, lac can produce red, crimson, pink, and deeper reddish shades.

Usman *et al.* (2023) studied lac-based dyeing of silk and viscose under microwave treatment. Their results showed that selected processing conditions produced substantial colour strength on silk, illustrating the potential of insect-derived anthraquinone dyes in textile coloration.



2.2.2. Cochineal

Cochineal is an insect-derived source of carminic acid, which can produce red and crimson shades. Its colour depends on the pH and the metal ions present during dyeing. Although it is a recognised natural colourant, its commercial use on silk must also consider raw-material supply, extraction requirements, animal-origin preferences, and fastness performance.

Animal-derived colourants can deliver strong shades, but their production may be constrained by biological supply, cost, and ethical or cultural considerations. They are therefore best assessed alongside plant-based alternatives rather than assumed to be universally preferable.

2.3. Microbial dyes

Certain fungi and bacteria produce coloured secondary metabolites, including pigments belonging to the classes of anthraquinones, azaphilones and other chromophoric compounds. Microbial dye production can potentially reduce dependence on seasonal agricultural sources and may allow controlled fermentation-based manufacture.

However, pigment production, extraction, purification, safety and dye–silk compatibility require individual assessment. Evidence supporting particular microbial pigments on silk should not automatically be generalised to the entire class of microbial dyes.

2.4. Agricultural and food-processing residues

Waste-derived colourants are important because they can connect textile production with circular-economy strategies. Potential feedstocks include pomegranate peel, onion skins, walnut husks, spent plant materials and discarded flowers.

Recent research has examined *Terminalia catappa* residues, *Bombaxceiba* waste flowers, and combined plant colourants derived from agricultural materials. These studies demonstrate opportunities for value addition, but the true environmental benefit depends on the residue's alternative uses, collection and transport requirements, extraction efficiency and management of the spent dye material.

Table 1. Representative natural dye sources and their potential applications on silk

Dye source	Principal colourants or class	Typical colour potential	Main consideration
Turmeric	Curcuminoids	Yellow, golden yellow	Light and pH sensitivity
Madder	Anthraquinones	Red, pink, rust	Mordant-dependent shade
Pomegranate peel	Tannins, polyphenols	Yellow, beige, brown	Variable extract composition
Beetroot	Betalains	Red-violet	Pigment stability
Marigold	Carotenoids	Yellow, orange	Pigment extraction and stability
Onion peel	Flavonoids	Yellow-brown	Batch-to-batch variation
Lac	Laccaic acids	Red, crimson	Biological sourcing and mordanting
Cochineal	Carminic acid	Red, crimson	Insect-derived raw material
Walnut husk	Polyphenolic colourants	Brown, dark brown	Extract composition and process control
<i>Sesbaniaaculeata</i> leaves	Plant-derived colourants	Extract-dependent	Optimisation of natural mordanting

Note: Colour descriptions indicate potential shades, not guaranteed outcomes. The final colour depends on pigment concentration, silk preparation, pH, mordant, temperature, and dyeing duration.

3. Chemistry of natural dyeing on silk

3.1. Structure and chemical properties of silk

Silk fibroin is a protein composed of amino acids arranged into ordered and less ordered regions. Its peptide bonds, amino groups, carboxyl groups, hydroxyl-containing side chains and other amino acid residues contribute to its interactions with dye molecules. The relative availability of these sites depends on fibre structure, processing history and the chemical characteristics of the dye.

Raw silk also contains sericin, a hydrophilic protein coating that can affect wetting, accessibility, lustre and dye uptake. Degumming is therefore often performed before dyeing when a clean, uniform silk substrate is required. However, the severity of degumming must be controlled to avoid unnecessary loss of fibroin or deterioration in fabric properties.

3.2. Dye–fibre interactions

Natural dyes generally interact with silk through several mechanisms:

- **Hydrogen bonding:** interactions between suitable dye functional groups and peptide bonds or polar side chains in fibroin.
- **Electrostatic interactions:** attraction between charged dye species and ionisable sites on the protein, depending on pH.
- **Van der Waals interactions:** weaker intermolecular forces that can contribute to adsorption and molecular association.
- **Hydrophobic interactions:** association between non-polar portions of certain colourants and relatively hydrophobic regions of the fibre.
- **Coordination or complex formation:** interaction of selected dye molecules with metal ions, potentially enabling additional associations with the fibre.

These mechanisms may operate together. Their relative importance depends on the molecular structure of the dye, the mordant chemist, and the conditions used during dyeing.

3.3. Influence of pH

The pH of the dye bath affects both the ionisation of fibroin functional groups and the chemical state of natural pigments. Under acidic conditions, some amino groups in silk become protonated, which can enhance attraction to suitable anionic dye species. Other dyes respond primarily through changes in pigment stability, solubility or metal complexation.

Consequently, there is no universal optimum pH for natural silk dyeing. For example, recent research on *Artemisia argyi* with an *Embllica officinalis* bio-mordant reported improved colour strength under specified acidic conditions, whereas rhubarb dye extraction and subsequent silk dyeing required different conditions.

3.4. Temperature and dyeing duration

Temperature affects pigment solubility, diffusion, adsorption and the rate at which dye–fibre interactions develop. Higher temperatures may improve dye transfer, but excessive heat can degrade heat-sensitive pigments and may adversely affect silk quality under unsuitable conditions.

The optimal dyeing duration similarly depends on the rate of pigment extraction and adsorption. Extending dyeing time beyond the point at which meaningful additional uptake occurs may increase energy consumption without producing a corresponding improvement in colour strength.

3.5. Colour strength and dye exhaustion

- Colour strength is commonly assessed using the Kubelka–Munk function:

$$K/S = \frac{(1-R)^2}{2R}$$

where (R) is the measured reflectance at the selected wavelength, (K) is the absorption coefficient and (S) is the scattering coefficient under the assumptions of the model.

A higher (K/S) value often indicates a deeper shade when comparable fabrics and measurement conditions are used. However, (K/S) values cannot be directly compared across studies unless measurement wavelengths, substrate characteristics, and testing conditions are sufficiently consistent.

- Dye exhaustion can be estimated from the dye-bath absorbance before and after dyeing, provided the measurement is calibrated and the solution follows the assumptions required for spectrophotometric analysis:

$$\text{Exhaustion (\%)} = \frac{C_0 - C_f}{C_0} \times 100$$

Here, C_0 and C_f represent the initial and final dye concentrations. When concentration is inferred from absorbance, suitable calibration and correction for changes in solution chemistry are necessary.

High exhaustion does not necessarily guarantee high colour strength or good fastness. The amount of dye removed from the bath, the amount retained after washing, and the resistance of the final colour to environmental exposure are distinct performance measures.

4. Natural dye extraction and dyeing techniques

4.1. Conventional aqueous extraction

Aqueous extraction remains a practical method for many plant-based dyes. Plant material is cleaned, dried where appropriate, and ground before extraction in water at a controlled temperature and duration. The extract is then filtered and used in the dye bath.

Advantages include simple equipment, accessible materials and the possibility of integrating the method with existing textile-processing infrastructure. Its disadvantages include potentially long extraction times, high water and energy requirements and inconsistent pigment yield when raw materials vary.

4.2. Solvent-assisted extraction

Water, aqueous ethanol and other suitable solvents can be used according to pigment polarity, stability, safety requirements and downstream processing needs. A solvent should be selected on the basis of extraction performance as well as toxicity, recovery, cost and environmental impact.

Although organic solvents may improve recovery for some pigments, their use can introduce additional separation and solvent-recovery requirements. Thus, a high extraction yield does not automatically translate into a more sustainable overall process.

4.3 Ultrasound-assisted extraction

Ultrasound introduces acoustic cavitation into the extraction medium. Bubble formation and collapse can generate localised shear forces that help disrupt plant structures and improve the release of colourants.

Potential benefits include reduced extraction time, improved mass transfer and lower processing temperatures for some dye systems. These benefits depend on ultrasound intensity, treatment duration, solvent composition, temperature and raw-material characteristics.

Recent work on beetroot dyeing and herbal yellow colourants for silk demonstrates the relevance of ultrasound-assisted processing. **Habib et al. (2024)**, for example, investigated an ultrasonic-assisted approach involving herbal colourants and bio-mordants for silk coloration.

5.4. Microwave-assisted extraction and dyeing

Microwave treatment provides rapid volumetric heating in suitable materials and can accelerate extraction or dyeing processes. Its performance depends on moisture content, solvent dielectric properties, vessel geometry, treatment time and power input.

- Lac dye: **Usman et al. (2023)** investigated microwave-assisted treatment of lac colourants for silk and viscose, reporting a maximum silk colour-strength value of (K/S=17.132) under one selected condition.
- Cassia fistula: **Mariam et al.(2024)** studied examined microwave-assisted extraction of brown pods and bio-mordanting for silk dyeing.
- Turmeric: A 2025 investigation examined microwave treatment and optimisation of turmeric-based yellow dyeing of silk.
- Binary plant colourants: A 2026 study reported a (K/S) value of 6.15 for a colourant combination based on thuja leaves and harmal seeds under optimised conditions.

These results demonstrate the potential of process intensification but should not be interpreted as a direct ranking of the dyes. Different pigments, equipment, substrates, dye concentrations, and testing conditions can produce substantially different (K/S) values.

4.5. Mordant-free dyeing

Mordant-free dyeing seeks to obtain acceptable colour depth and durability without a separate mordant. It can reduce processing steps and avoid the need for additional mordant chemicals, although the dye itself may still require stabilisation or careful process control.

Balakrishnan (2024) investigated *Basella alba* fruit colourants for silk using a mordant-free approach. The study highlights the potential of selected natural pigments to colour silk without conventional mordanting, although performance must be assessed for each dye–fibre combination.

4.6. Other emerging techniques

Emerging approaches include enzyme-assisted extraction, supercritical-fluid extraction, plasma-assisted surface modification, and non-aqueous dyeing. Their relevance to natural silk dyeing varies, and the evidence base is not equally developed for every technique.

Younas *et al.* (2026) investigated turmeric-derived curcumin in a decamethyl -cyclopentasiloxane-based non-aqueous system, with an emphasis on reducing water consumption. Such approaches require assessment of the full solvent life cycle, recovery efficiency, worker safety, and end-of-process residues before environmental benefits can be established. A mordant is a substance used to improve dye attachment, influence shade, or increase colour durability. Depending on the dye system, a mordant may form a coordination complex with the pigment, modify its solubility, or change its interaction with the fibre.

Table 2. Comparison of dye extraction and dyeing methods

Method	Potential benefit	Main limitation
Conventional aqueous extraction	Simple equipment and accessible materials	Potentially high water and energy demand
Solvent-assisted extraction	Improved recovery of selected pigments	Solvent recovery and safety requirements
Ultrasound-assisted extraction	Faster mass transfer in suitable systems	Equipment settings and scale-up need optimisation
Microwave-assisted extraction	Rapid heating and potentially shorter processing	Uneven heating and energy-control requirements
Mordant-free dyeing	Fewer processing steps	Fastness may be inadequate for some dyes
Enzyme-assisted processing	Potentially selective, mild treatment	Enzyme cost, stability, and process compatibility
Non-aqueous dyeing	Potential water savings	Solvent recovery and life-cycle performance must be demonstrated

5. Mordants and their role in silk dyeing

Mordanting can be beneficial but should not be considered mandatory for every natural dye. Some dyes exhibit useful affinity for silk without a mordant, while others require additional treatment to achieve acceptable colour strength or fastness.

Islam *et al.* (2025) reviewed the functions and environmental implications of metallic and bio-based mordants, highlighting the potential of plant-derived alternatives as well as challenges related to their availability, cost and standardisation.

5.1. Metallic mordants

Common metallic mordants investigated in textile dyeing include alum-based aluminium salts, ferrous sulfate and copper salts. Their effects depend on metal-ion concentration, the pigment's coordination chemistry and the sequence of treatment.

- **Aluminium salts:** Often used to develop or retain relatively bright shades.
- **Iron salts:** Can deepen shades or shift them toward grey, olive, brown or darker tones.
- **Copper salts:** Can modify shade and improve dye uptake for selected systems but require careful environmental assessment.

Metallic mordants should not be treated as environmentally equivalent. Their potential toxicity, persistence, concentration in wastewater and disposal requirements differ. The use of a natural dye with a hazardous or poorly managed mordant may reduce or eliminate the environmental advantage expected from replacing a synthetic dye.

5.2. Bio-mordants

Bio-mordants are materials derived from biological sources that can promote dye uptake or alter colour development. They often contain tannins, polyphenols, or other compounds capable of interacting with both colourants and protein fibres.

Examples include extracts from:

- *Phyllanthusemblica* (Indian gooseberry or amla).
- *Terminalia chebula* (myrobalan).

- Pomegranate peel.
- Tannin-rich plant materials.
- Selected fruit and leaf extracts.

A recent silk-dyeing study by **Feng et al. (2025)** investigated *Phyllanthusemblica* extract as a natural mordant for silk dyed with *Artemisia argyi*. Under the study's reported conditions, the (K/S) value increased from 2.82 to 5.05 and washing and rubbing fastness improved by approximately half a grade. These results support the potential of plant-derived mordants, although they do not establish equivalent performance for all dye systems.

5.3. Mordanting sequences

Three main sequences are used in natural dyeing.

Pre-mordanting

The silk is treated with the mordant before dyeing. This may establish binding sites or modify fibre–dye interactions before the colourant is introduced.

Meta-mordanting (simultaneous mordanting)

The mordant and dye are introduced into the same bath. This can reduce the number of separate processing stages but requires control of precipitation, pH, and competition between dye–metal and dye–fibre interactions.

Post-mordanting

The dyed silk is treated with the mordant afterward. This method can substantially change the final shade and may improve retention for selected dye systems.

5.4. Lemon juice and other acidic treatments

Lemon juice has been investigated as a natural mordanting or pH-adjusting agent in certain silk-dyeing formulations. Younas et al. reported improved colour strength and selected fastness properties for *Sesbaniaaculeata* leaf dyeing of silk using lemon juice in a meta-mordanting process. The reported dye exhaustion was 31% under the studied conditions.

However, acidity adjustment should not automatically be described as true mordanting. Citric acid and other organic acids can alter dye-bath pH without necessarily forming a stable dye–mordant–fibre complex. Their function must be established for each formulation.

5.5. Environmental assessment of mordants

Bio-mordants can reduce dependence on certain metal salts, but their environmental performance is not guaranteed. Important factors include the source of the plant material, extraction requirements, biological oxygen demand of the effluent, chemical oxygen demand, residual colour and the fate of spent mordant solutions.

A robust evaluation should compare the entire dyeing process rather than focusing only on the biological origin of the mordant. This is especially important when a bio-mordant requires substantial extraction energy or large quantities of water.

6. Colour quality and fastness assessment

The commercial suitability of naturally dyed silk depends on reproducible colour, acceptable fastness, fabric integrity, and compliance with the intended end use.

6.1. Washing fastness

Washing fastness describes resistance to colour change and staining during laundering. It depends on dye affinity, dye solubility, fixation, mordant chemistry, and the effectiveness of post-dye washing.

Weakly attached colourants may be removed during washing, leading to shade loss or staining of adjacent textiles. Washing tests should use a recognised standard, such as the relevant ISO 105-C series, with the specific method reported.

6.2. Light fastness

Light fastness measures resistance to colour change caused by light exposure. Natural pigments differ substantially in their photochemical stability. Some colourants may fade through oxidation, bond cleavage, or other degradation pathways.

Light fastness is especially important for curtains, decorative silk, and garments exposed to sunlight. Suitable tests should follow an identified method from the ISO 105-B series or another recognised equivalent.

6.3. Rubbing fastness

Rubbing fastness evaluates colour transfer under dry and wet friction. It is influenced by surface deposits, fibre smoothness, dye fixation, and the amount of residual unfixed colourant.

Tests from the ISO 105-X series can help assess suitability for garments and other products that experience repeated contact.

6.4. Perspiration fastness

Perspiration fastness is relevant for silk clothing that comes into contact with sweat. Both acidic and alkaline perspiration conditions may influence colour stability. Evaluation using an appropriate ISO 105-E method is therefore important for wearable products.

6.5. Instrumental colour analysis

Colour measurement should include the CIE coordinates, colour difference where relevant, and reflectance-based colour strength. Reporting the measurement instrument, illuminant, observer angle, measurement geometry, and specimen preparation improves reproducibility.

6.6. Fabric and chemical characterisation

Additional measurements can help establish whether the dyeing treatment changes the silk substrate or introduces useful functional properties:

- Fourier-transform infrared spectroscopy (FTIR) to examine changes in chemical bonding environments.
- Scanning electron microscopy (SEM) to inspect surface morphology.
- UV–visible spectroscopy to characterise pigment absorption and dye-bath changes.
- Tensile testing to identify possible damage to silk.
- Antibacterial and antioxidant assays when functional performance is claimed.
- Standardised wash and light exposure tests to verify durability.

Functional properties must be measured independently of colour strength. For example, antibacterial activity reported for a dyed fabric does not by itself demonstrate long-term activity after repeated washing or prove safety for every intended skin-contact application.

7. Sustainable applications of naturally dyed silk

7.1. Sustainable fashion and premium textiles

Naturally dyed silk can be used in scarves, apparel, accessories, home furnishings, and specialty textiles where colour variation and material provenance may contribute to product value. Small-scale craft production and premium textile markets may be particularly suitable where batches can be controlled and shade variation is acceptable.

7.2. Traditional textile and artisan production

Natural dyeing has historical importance in many textile traditions. Scientific optimisation can support traditional practices by improving reproducibility, documenting extraction conditions, and reducing the use of undesirable chemicals without eliminating the cultural value of local materials and methods.

7.3. Agro-waste valorisation

Agricultural and food-processing residues can provide additional value when they contain recoverable colourants or tannins. Their use may reduce reliance on purpose-grown dye crops and create opportunities for rural processing enterprises.

However, a residue should not be considered waste-free or impact-free simply because it originates from an agricultural by-product. Collection, drying, storage, extraction, transport, and disposal all contribute to its environmental footprint.

7.4. Multifunctional silk textiles

Some natural dye systems can contribute properties beyond colour, including ultraviolet absorption, antioxidant activity, and antibacterial effects. Recent research on lac and other natural colourants has explored such additional functionalities in silk fabrics.

These applications are promising, but functional claims require standardised testing, suitable controls, assessment of durability, and consideration of possible skin-contact or environmental risks.

7.5. Water- and energy-efficient dyeing

Ultrasound, microwave treatment, and selected non-aqueous methods may reduce processing time or water consumption in particular systems. Their benefits should be verified through measured water and energy use per unit of saleable fabric rather than inferred solely from shorter processing times.

A process that saves water but requires energy-intensive equipment or problematic solvents may not offer a net environmental benefit.

7.6. Sustainable silk production in India

India has an established silk sector and diverse botanical resources, creating opportunities to investigate natural dyeing using locally available materials. Examples include turmeric, pomegranate peel, onion skins, marigold, and tannin-rich plant residues.

For practical adoption, local studies should assess seasonal availability, pigment standardisation, cost, water quality, fastness, and compatibility with existing silk-processing equipment. Regional research is especially valuable when it combines laboratory dyeing with pilot-scale production and wastewater analysis.

8. Challenges, research gaps and future directions

Despite increasing interest in natural dyes, several technical and sustainability challenges remain.

8.1. Raw-material variability

Natural pigment concentrations may vary with species, cultivar, geography, maturity, season, storage, and extraction method. Such variability complicates shade matching and industrial reproducibility.

Future studies should develop standardised raw-material characterisation, extraction yields, and pigment concentration measurements.

8.2. Inconsistent fastness

Some natural dyes show limited resistance to light, washing, or rubbing. Bio-mordants can improve performance in selected systems, but their effects are dye-specific. Research should identify the mechanisms of colour loss and develop durable dyeing approaches that do not require excessive chemical inputs.

8.3. Incomplete environmental evaluation

Many laboratory studies focus on colour strength and fastness without measuring the complete environmental impact of the process. Future investigations should quantify water consumption, energy demand, chemical inputs, effluent characteristics, and residual biomass.

Life-cycle assessment (LCA) and life-cycle costing can help determine whether a natural dye system provides genuine environmental and economic benefits relative to a suitable synthetic-dye benchmark.

8.4. Scale-up and process reproducibility

Laboratory methods may not translate directly to industrial dyeing because heating patterns, liquor ratios, fabric movement, mass transfer, and treatment uniformity change with scale. Scale-up studies should include equipment energy consumption, batch reproducibility, production rate, and shade consistency.

8.5. Standardisation of bio-mordants

Plant extracts can contain complex mixtures whose composition changes between batches. Developing standardised bio-mordant formulations will require chemical characterisation, performance specifications, and stability testing.

8.6. Improved extraction technologies

Ultrasound and microwave treatment warrant further study, but comparisons should include energy per unit of extracted pigment, yield, solvent requirements, and the quality of the resulting dye. Optimisation should target overall process efficiency rather than colour strength alone.

8.7. Safer and more durable colourants

Future research should explore dye–fibre interactions, pigment stabilisation, and safer mordant alternatives. Any improvement should be evaluated for toxicity, persistence, fastness, and fabric integrity.

8.8. Digital shade management and process control

Spectrophotometry, statistical design of experiments, and data-driven process control can help reduce variation in natural dyeing. By relating raw-material properties and processing variables to final colour, these approaches may improve shade prediction and reduce rejected batches.

CONCLUSION

Natural dyeing of silk is a promising area of textile research that brings together renewable colourants, protein-fibre chemistry, traditional knowledge and modern process engineering. Plant-derived pigments, animal-derived colourants, microbial pigments and agricultural residues offer diverse possibilities for silk coloration. Their practical performance depends on dye chemistry, fibre preparation, extraction efficiency, bath conditions, mordanting strategy and the desired fastness properties.

Recent research demonstrates that ultrasound-assisted and microwave-assisted methods, bio-mordants, waste-derived colourants and optimised dyeing conditions can improve selected aspects of silk coloration. However, improvements reported for one dye system cannot be assumed to apply to all natural dyes. Colour strength, exhaustion, fastness, fabric quality and environmental impact must be evaluated separately.

The transition towards genuinely sustainable silk dyeing requires more than substituting natural colourants for synthetic ones. It requires safer mordants, reproducible raw materials, efficient extraction, reduced water and energy consumption, appropriate wastewater treatment and credible life-cycle assessment. A combined approach integrating fibre science, analytical chemistry, textile engineering and sustainability assessment offers the strongest basis for developing reliable, scalable and environmentally responsible natural dyeing systems.

REFERENCES

1. Adeel, S., Kamran, M., Afzaal, M., Aftab, M., Munawar, K. S., Khan, A., & Hussain, F. (2026). Sustainable dyeing and mordanting of silk with a binary colorant from agro-waste material. *Molecules*, 31(18), 3253.
2. Adeel, S., Rehman, F.-U., Rafi, S., Zia, K.M., Zuber, M., 2019. Environmentally friendly plant-based natural dyes: extraction methodology and applications. In: *Plant and Human Health*, vol. 2. *Springer International Publishing*, Cham, pp. 383–415.
3. Balakrishnan, S. (2024). Silk fabric dyeing with *Basella alba* (Sri Lankan green spinach fruit) natural dyes: Mordant-free dyeing approaches. *Industrial Crops and Products*, 222, 119337.
4. Bilal, U., Adeel, S., & Khatkhat, S. P. (2026). Innovative application of extracted binary colorant from henna and walnut for dyeing of mordanted silk.
5. Feng, L., Ye, A., Yu, X., & Chen, Z. (2025). Eco-friendly dyeing of silk fabric by using *Artemisia argyi* as natural dye and *Phyllanthus emblica* as natural mordant. *RSC Advances*, 15(57), 49432–49440.
6. Habib, N., Adeel, S., Ibrahim, M., et al. (2024). Eco-friendly ultrasonic-assisted appraisal of herbal-based yellow natural colorant for silk dyeing. *Energy Science & Engineering*, 12, 5061–5077.
7. Huang, Q., Wang, Z., Zhao, L., Li, X., Cai, H., Yang, S., Yin, M., & Xing, J. (2024). Environmental dyeing and functionalization of silk fabrics with natural dye extracted from lac. *Molecules*, 29(10), 2358.
8. Islam, S., Jalil, M. A., Belowar, S., Saeed, M. A., Hossain, S., Rahamatolla, M., & Ali, S. (2025). Role of mordants in natural fabric dyeing and their environmental impacts. *Environmental Science and Pollution Research*, 32(2), 452–468.
9. Khatun, M. H., Rabbi, M. A., Ahmed, F., Kadri, H. J., Maitra, B., Al-Amin, M., Rasel, M. Z. U., & Akter, R. (2025). Transforming waste into eco-friendly dye: A study of silk dyeing with *Terminalia catappa* using metal mordants and bio-mordants. *Sustainable Chemistry One World*, 8, 100143.
10. Lara, L., Cabral, I. and Cunha, J., 2022. Ecological approaches to textile dyeing: a review. *Sustainability*, 14(14), p.8353.
11. Mariam, Y., Shahid A., Muhammad, Z., Rony, M. and Muhammad, I. 2024. Enhancing silk dyeing with eco-friendly colorant extracted from *Cassia fistula* brown pods using green mordants. *Sustainable Chemistry and Pharmacy*.37: 01410.

12. Mia, et al. (2025). Ultrasonic assisted environmentally friendly extraction of natural dyes from *Beta vulgaris* for the coloration of silk fabric using different mordants. *Energy Science & Engineering*, 13(1), 323–334.
13. Pizzicato B, Pacifico S, Cayuela D, Mijas G, Riba-Moliner M. Advancements in Sustainable Natural Dyes for Textile Applications: A Review. *Molecules*.28 (16):5954.
14. Sun, X., Pan, G., Li, X., Huang, Q., Ma, X., Sheng, M., & Yin, M. (2026). Multifunctional dyeing process and characterization of silk fabric based on natural colorant of rhubarb. *Molecules*, 31(7), 1165.
15. Uddin, M. A., Rahman, M. M., Haque, A. N. M. A., Smriti, S. A., Datta, E., Farzana, N., Chowdhury, S., Haider, J., & Sayem, A. S. M. (2022). Textile colouration with natural colourants: A review. *Journal of Cleaner Production*, 349, 131489.
16. Usman, M., Rehman, F. U., Afzal, M., Javed, M., Ibrahim, M., Amin, N., Adeel, S., Imran, M., & Mansour, R. (2023). Sustainable appraisal of lac (*KerriaLacca*) based anthraquinone natural dye for chemical and bio-mordanted viscose and silk dyeing. *Science progress*, 106(4).
17. Younas, U., Safdar, F., Maqsood, H. S., Bashir, U., Jan, K., Rehman, A., & Iqbal, K. (2026). A sustainable approach for dyeing silk fabric using dye and mordant extractions from natural resources. *Pigment & Resin Technology*, 55(2), 254–265.
18. Yusuf, M., Mohammad, F., Shabbir, M., 2017a. Eco-friendly and effective dyeing of woolwithanthraquinone colorants extracted from *Rubiocordifolia* roots: optimization,colorimetric and fastness assay. *J. King Saud Univ.* 29, 137–144.
19. Zahid, A. A. S. M., Islam, M. R., Maitra, B., Al-Amin, M., Azad, A. K., &Khatun, M. H. (2025). Dyeing of silk and cotton using facile and green extracted natural dye from *Bombaxceiba*. *Journal of the Indian Chemical Society*, 102(2), 101572.