ISSN: 2230-9926

Available online at http://www.journalijdr.com

IJDR

International Journal of Development Research
Vol. 16, Issue, 10, pp.71072-71079, October, 2026
https://doi.org/10.37118/ijdr.31231.10.2026



REVIEW ARTICLE

OPEN ACCESS

SUSTAINABLE NATURAL COLOURATION OF KHADI COTTON: NATURAL DYES, BIO-MORDANTS, RESOURCE-EFFICIENT PROCESSING AND CIRCULARITY PERSPECTIVES

Natarajan Arunraaj[1] and Dr. P. Senthilkumar[2]

Department of Textile Technology, PSG College of Technology, Coimbatore 641 004, India

ARTICLE INFO

Article History:

Received 20th July, 2026
Received in revised form
25th August, 2026
Accepted 15th September, 2026
Published online 31st October, 2026

Key Words:

Khadi Cotton; Natural Colourants; Natural Dyes; Bio-mordants; Sustainable Textile Coloration; Pad-Dry-Steam; Colour Strength; Colourfastness; Circular Economy; Resource Efficiency.

Corresponding author:
Er. Natarajan Arunraaj

ABSTRACT

The transition towards more sustainable textile production has renewed scientific interest in natural colorants and low-impact coloration technologies. Textile wet processing, particularly dyeing and finishing, is associated with substantial water, energy and chemical requirements, making coloration an important target for cleaner production strategies (Hussain, 2018; Khattab, 2020; Haji, 2020; Uddin, 2022). Natural colourants obtained from plants, microorganisms, animals, minerals and agro-industrial residues have consequently attracted renewed attention because of their renewable origin, chemical diversity and potential for biodegradability and waste valorization (Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a; Vankar, 2000). However, natural origin alone does not establish environmental superiority. Extraction conditions, mordant selection, dye–fibre affinity, water and energy requirements, colour reproducibility, fastness and scalability must be evaluated together (Pizzicato, 2023; Salauddin Sk M., 2021; Benli, 2024; Mansour, 2018; Phan, 2021). Khadi cotton provides a distinctive context for this transition because its hand-spun and handwoven production system is strongly associated with decentralized manufacturing, artisanal knowledge, rural employment and cultural identity. Previous life-cycle research on the khadi-handloom system has demonstrated the importance of integrating environmental, socioeconomic and cultural dimensions when assessing its sustainability (Bhalla, 2018). This review critically examines natural colouration of cotton with particular emphasis on its relevance to khadi. The chemistry and application of important natural colorant classes, including indigoids, anthraquinones, flavonoids, tannins and curcuminoids, are discussed together with the growing use of agricultural and food-processing residues as dye resources (Pizzicato, 2023; Salauddin SK M., 2021; Repon, 2024; Vankar, 2000; Phan, 2020). Attention is given to madder indigo & pomegranate peels because of their historical significance, chemical diversity and demonstrated applicability to cellulosic textiles (Vankar, 2008; Ajmal, 2014; Otaviano, 2023; Li, 2022). The roles of conventional mordants, Bio-mordants and fibre modification strategies are critically assessed, with emphasis on their effects on colour strength, shade development and Colourfastness (Benli, 2024; Repon, 2024b; Thakker, 2022; Rahman, 2023; Shahmoradi Ghaheh, 2021; Nazir, 2022; Hosen, 2021). Conventional exhaust dyeing is compared with resource-efficient approaches such as ultrasound-assisted dyeing, surface modification, padding and pad-steam processing (Vankar, 2007; Zia, 2019; Cai, 2022; Khattak, 2023; Baig, 2021; Wang, 2022). Pad-dry-steam processing is identified as a potentially valuable technology for decentralized khadi production because controlled liquor application can reduce the volume of dye liquor requiring heating and discharge while potentially improving shade reproducibility. Nevertheless, the associated drying and steaming energy must be included in any quantitative sustainability assessment. Colour strength, CIELAB coordinates, colour difference and washing, rubbing and light fastness are identified as essential indicators for evaluating the technological viability of naturally colored khadi (Salauddin Sk M., 2021; Repon, 2024a; Ma, 2020). The review further examines circular-economy opportunities associated with agricultural residues, rural livelihood generation and small-scale production (Bhalla, 2018; Agnhage, 2017). Major research gaps include inconsistent extraction procedures, insufficient chemical characterization of natural colourants, incomplete reporting of colourimetric data, limited standardization of fastness testing, inadequate resource balances, insufficient pilot-scale validation and limited integrated life cycle and techno-economic assessments. The review proposes a research framework in which colorant chemistry, extraction, fibre modification, application technology, colour performance, durability, resource consumption, environmental impact and socioeconomic feasibility are optimized simultaneously. The future of sustainable khadi coloration therefore lies not simply in replacing synthetic dyes with natural dyes, but in combining traditional textile knowledge with modern colour science, process engineering and life cycle thinking.

Copyright©2026, Natarajan Arunraaj and Dr. P. Senthilkumar. 2026. *This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.*

Citation: Natarajan Arunraaj and Dr. P. Senthilkumar. 2026. *"Sustainable Natural Colouration of Khadi Cotton: Natural Dyes, Biomordants, Resource-Efficient Processing and Circularity Perspectives". International Journal of Development Research, 16, (10), 71072-71079.*

INTRODUCTION

The textile industry is under increasing pressure to reduce its consumption of water, energy and chemicals while maintaining product quality, colour reproducibility and economic competitiveness. Wet processing is particularly important in this context because dyeing and finishing requires substantial quantities of water and thermal energy and generate wastewater containing residual dyes, auxiliaries and other process chemicals (Hussain, 2018; Khattab, 2020). Reviews of textile wet processing have consequently identified water conservation, cleaner chemistry and process intensification as major routes towards reducing the environmental burden of textile production (Hussain, 2018; Khattab, 2020; Haji, 2020). The environmental concerns associated with textile coloration have contributed to renewed interest in natural dyes. Natural colourants can be obtained from plants, animals, microorganisms, minerals and, increasingly, agricultural and food-processing residues (Uddin, 2022; Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a). Their potential advantages include renewable feedstocks, biodegradability of many naturally occurring compounds, opportunities for local resource utilization and the possibility of converting low-value biomass into higher-value textile products (Salauddin Sk M., 2021; Agnhage, 2017). Nevertheless, natural dyes should not automatically be regarded as environmentally benign. Their sustainability depends on the complete production pathway, including raw-material acquisition, extraction, mordanting, dye application, washing, drying, fixation and waste management (Pizzicato, 2023; Salauddin Sk M., 2021; Ul-Islam, 2020). This distinction is important because natural colourants often have lower affinity for textile substrates than optimized synthetic dyes. Consequently, natural dyeing may require mordants, auxiliaries, repeated applications or extensive after-washing to obtain commercially acceptable colour depth and fastness (Pizzicato, 2023; Repon, 2024a; Benli, 2024). The requirement for mordants can introduce additional environmental concerns, particularly when metallic salts are employed (Benli, 2024; Repon, 2024b).

Recent research has therefore increasingly focused on Bio-mordants, fibre modification, enzymatic pretreatment, ultrasound, plasma and other process-intensification technologies (Benli, 2024; Rahman, 2023; Shahmoradi Ghaheh, 2021; Nazir, 2022; Hosen, 2021; Vankar, 2007; Zia, 2019). The renewed interest in natural colourants is also closely associated with circular-economy strategies. Agro-industrial residues such as fruit peels, cereal residues, leaves and other biomass streams may contain useful chromophoric compounds and can potentially be converted into textile colourants rather than being treated exclusively as waste (Salauddin Sk M., 2021; Agnhage, 2017). Pomegranate peel, orange peel, onion-derived residues, sawdust, cork by-products and other residues have been investigated for textile coloration (Ajmal, 2014; Otaviano, 2023; Li, 2022; Agnhage, 2017; Kandasamy, 2021; Coelho Pinheiro, 2023). Such approaches are particularly attractive where the residue is locally available and requires relatively low-intensity processing. Khadi represents a particularly relevant textile system within this sustainability transition. Unlike mass-produced industrial cotton, khadi is traditionally associated with hand spinning and hand weaving and therefore embodies a decentralized production model. Life-cycle research on the khadi-handloom system has demonstrated the importance of evaluating environmental, social and cultural dimensions together rather than considering energy or material use alone (Bhalla, 2018). The decentralized character of khadi may also provide opportunities for small-batch coloration, local resource utilization and rural employment. However, the environmental advantages associated with handloom production should not automatically be extended to the coloration stage. Dye extraction, mordanting, dyeing, washing and drying may introduce substantial resource requirements. Therefore, sustainable khadi should be considered as an integrated system encompassing fibre production, yarn formation, weaving, coloration, finishing, use and end-of-life management (Bhalla, 2018). A second challenge is product quality. Contemporary textile markets require reproducible colour, acceptable colour strength and sufficient resistance to washing, rubbing and light exposure. Natural dyes often exhibit variability in shade and fastness because of differences in botanical source, geographical origin, maturity, extraction method, dye concentration and application conditions (Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a). Standardization of colour measurement and process parameters is therefore essential for moving natural dyeing from artisanal experimentation towards reproducible commercial production. Recent reviews emphasize that insufficient colourimetric characterization and process standardization remain major barriers to the industrial adoption of natural dyes (Salauddin Sk M., 2021; Repon, 2024a).

Similarly, contemporary reviews of Bio-mordants identify improvement of dye–fibre affinity and Colourfastness as important research objectives (Benli, 2024; Repon, 2024b). These observations suggest that the future of natural-dyed khadi requires a combination of traditional knowledge and quantitative textile science. Among alternative application technologies, padding and pad-steam processing are particularly relevant because they allow controlled application of relatively small quantities of dye liquor. Research on pad-steam coloration and related controlled application processes demonstrates the technical potential of these technologies, although the energy requirement for drying and steaming must be considered (Khattak, 2023; Baig, 2021; Wang, 2022). The objective of this review is therefore to critically evaluate the scientific basis for sustainable natural colouration of khadi cotton. The review focuses on five interconnected dimensions: (i) natural-colorant chemistry and sources; (ii) dye–cellulose interactions and mordanting; (iii) resource-efficient coloration technologies; (iv) colour strength and fastness performance; and (v) environmental, circular-economy and socioeconomic implications. The review specifically addresses the following questions:

1. Which natural colorant classes are most relevant to cotton and khadi?
2. How do colorant chemistry, mordanting and fibre modification influence colour performance?
3. What potential advantages do padding and pad-dry-steam technologies offer?
4. Can agricultural residues contribute meaningfully to circular natural coloration?
5. What evidence is currently available regarding environmental and socio-economic sustainability?
6. Which methodological gaps must be addressed before natural-dyed khadi can be reliably scaled?

REVIEW METHODOLOGY

A structured literature-review approach was adopted to identify peer-reviewed studies concerning natural colourants, cotton coloration, khadi and handloom textiles, Bio-mordants, resource-efficient dyeing, colour measurement, fastness, circular economy and environmental assessment. Literature searches focused on combinations of keywords including “natural dyes”, “natural colourants”, “cotton dyeing”, “khadi”, “handloom”, “Bio-mordants”, “agricultural waste dyes”, “pomegranate peel”, “madder”, “indigo”, “pad dyeing”, “pad-steam”, “colour strength”, “K/S”, “CIELAB”, “colour fastness”, “sustainable textile dyeing”, “water consumption”, “energy consumption” and “life-cycle assessment”. Peer-reviewed journal articles indexed in Web of Science and/or Scopus were prioritized.

Foundational literature was retained where it provided essential information on natural-dyes chemistry, textile coloration, extraction or environmental assessment. Recent reviews published during 2020–2025 were preferentially used to identify current research trends and research gaps (Uddin, 2022; Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a; Vankar, 2000; Benli, 2024; Repon, 2024b). The evidence was classified into four principal categories:

- Chemical evidence: natural-colorant composition, chromophore class, extraction and dye–fibre interactions.
- Technical evidence: colour strength, CIELAB coordinates, colour difference, fixation and fastness.
- Process evidence: liquor ratio, water consumption, energy demand, extraction intensity and wastewater generation.
- Sustainability evidence: life-cycle impacts, waste valorization, economics, rural employment and scalability.

This distinction is important because a process demonstrating high colour strength does not necessarily demonstrate environmental superiority. Similarly, the process of using a renewable colorant does not necessarily have a lower life-cycle impact.

Khadi Cotton and Its Sustainability Context: Khadi represents an unusual intersection of textile technology, cultural heritage and decentralized production. Its identity is associated with hand spinning and hand weaving, making it fundamentally different from industrially manufactured cotton fabrics. The production chain can involve farmers, spinners, weavers, dyers, garment makers and traders, thereby distributing economic activity across rural communities (Bhalla, 2018). The sustainability significance of khadi should therefore be understood in multidimensional terms. Environmental performance is only one component; livelihood generation, cultural preservation, decentralized value creation and artisanal knowledge are also relevant. The integrated life-cycle assessment of the khadi-handloom industry demonstrated that environmental and socioeconomic factors should be considered simultaneously when evaluating the system (Bhalla, 2018). From a material perspective, cotton is a cellulose-rich fibre containing abundant hydroxyl groups. These functional groups provide opportunities for hydrogen bonding and other intermolecular interactions but do not guarantee strong affinity for all-natural colourants. Many natural colourants therefore require mordanting, fibre modification or process intensification to obtain commercially useful shades (Benli, 2024; Thakker, 2022; Rahman, 2023). The coloration stage consequently represents an important opportunity for improving the sustainability of khadi. If low-water and low-chemical coloration can be developed without compromising artisanal quality, the environmental benefits associated with decentralized production could be strengthened. However, the term "eco-friendly khadi" should not be applied solely because the fabric is handwoven. The dye source, extraction method, mordant, liquor ratio, washing procedure and energy requirements must also be assessed.

Natural Colourants: Chemistry, Sources and Textile Relevance: Natural colourants comprise a chemically diverse group of compounds. Plant-derived colourants are particularly important for textile applications and include indigoids, anthraquinones, flavonoids, tannins, curcuminoids and related phenolic compounds (Uddin, 2022; Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a; Phan, 2020). The chemical class of a colorant strongly influences its solubility, adsorption, fixation mechanism, shade and fastness. Consequently, natural dyes cannot be treated as a single technological category.

Indigoid colourants: Indigo is an important natural vat colorant for cotton. Its application differs fundamentally from that of many water-soluble plant extracts because the pigment undergoes a reduction–oxidation sequence during dyeing. The reduced form is soluble and can penetrate the substrate before oxidation regenerates the characteristic blue indigo pigment. The historical importance of indigo demonstrates that natural colouration can achieve durable and commercially significant shades. However, natural indigo production itself can involve cultivation, fermentation and processing requirements that should be considered when evaluating sustainability.

Anthraquinone colourants: Madder is a major natural source of anthraquinone colourants, including alizarin-related compounds. Madder has relevance to cotton because it provides red to orange-red shades that are difficult to obtain from many other natural sources. Research on madder coloration of cotton demonstrates that fixation can be improved through fibre modification and crosslinking strategies. Cai *et al*. investigated ethylene glycol diglycidyl ether crosslinking in madder-dyed cotton and demonstrated the relevance of modifying the fibre–dye system rather than relying exclusively on increased dye or mordant concentrations (Cai, 2022).

Polyphenolic and tannin-rich colourants: Pomegranate peel, tea-derived materials, bark, leaves and other biomass sources contain polyphenols and tannin-related compounds that can provide yellow, brown, orange and related shades. Pomegranate peel is particularly attractive because it represents a food-processing residue rather than a dedicated dye crop (Ajmal, 2014; Otaviano, 2023). Otaviano *et al*. investigated pomegranate-peel extract for cotton coloration and evaluated its physicochemical characteristics, Colourfastness and functional properties (Otaviano, 2023). Earlier research demonstrated that radiation treatment could modify pomegranate-peel colorant characteristics and improve extraction and dyeing performance (Ajmal, 2014).

Curcuminoid colourants: Turmeric is a widely available source of curcuminoids and provides yellow coloration. Its use of cotton has been investigated using conventional and intensified processes. Ma *et al*. demonstrated ultrasound-assisted ultralow-liquor-ratio dyeing of cotton using natural turmeric dye, illustrating the relevance of process intensification for reducing liquor requirements (Ma, 2020). However, turmeric and other curcuminoid colourants may have limitations in light stability. Consequently, the suitability of a natural colorant must be assessed according to the intended product application rather than colour development alone.

Agricultural and Food-Processing Residues as Natural Colorant Resources: The conversion of agricultural and food-processing residues into textile colourants represents one of the strongest links between natural dyeing and circular-economy principles. Phan *et al*. reviewed non-food applications of natural dyes derived from agro-food residues and identified textile coloration as an important valorization pathway (Agnhage, 2017). Such residues can include fruit peels, seed coats, leaves, cereal residues and wood-processing by-products. Pomegranate peel is one example. Orange peel has also been investigated for cotton dyeing, with tannic acid used as a mordant to improve coloration (Li, 2022).

Similarly, cotton and silk coloration using Pterocarpus indicus sawdust has been investigated following ultrasound-assisted extraction, demonstrating the possibility of converting timber-industry waste into textile colourants (Coelho Pinheiro, 2023). Cork-industry by-products have likewise been evaluated as natural textile dyes. Coelho Pinheiro *et al*. demonstrated the potential of cork-processing residues for coloration of textile fibres and highlighted their relevance to industrial residue valorization (Chemat, 2017). These studies support a broader circular pathway: waste biomass → extraction → colorant → textile application → higher-value product. However, residue valorization should not automatically be considered sustainable. Collection, drying, grinding, extraction and transportation can require energy and materials. Therefore, the environmental advantage depends on whether the residue can be obtained with relatively low additional burden.

Natural Dye Extraction and Green Extraction Technologies:

Extraction is one of the most important stages to control the quality and sustainability of natural colourants. Conventional extraction can require prolonged heating, high liquor ratios and repeated processing. These requirements may offset some of the environmental benefits associated with renewable colorant sources (Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a). Ultrasound-assisted extraction has attracted considerable attention because acoustic cavitation can enhance mass transfer and accelerate extraction. Chemat *et al*. reviewed ultrasound-assisted extraction and identified its potential for improving extraction efficiency while reducing processing time and solvent requirements (Bosiljkov, 2017).

Microwave-assisted extraction represents another intensification strategy. Such technologies can accelerate heating and potentially reduce extraction time, although their actual environmental performance depends on electrical energy consumption and extraction yield. The choice of extraction solvent is equally important. Water is attractive for small-scale textile production because it is inexpensive, comparatively safe and accessible. However, aqueous extraction can be less selective than some organic-solvent systems. Green solvents and natural deep eutectic solvents have consequently emerged as potential alternatives for extracting bioactive compounds and colourants (Thakur, 2022; Zhang, 2022). For decentralized khadi production, the most suitable extraction method may not be the technologically most sophisticated one. The preferred system should combine adequate yield with simple equipment, low energy requirements, low toxicity, reliable reproducibility and compatibility with local resources.

Dye–Cellulose Interactions: Cotton is composed primarily of cellulose, whose hydroxyl-rich structure enables hydrogen bonding with suitable dye molecules. However, the relatively hydrophilic cellulose surface does not provide strong affinity for all-natural colourants. This explains why many natural dyes exhibit lower substantivity on cotton than on protein fibres. The resulting problems include low colour depth, poor fixation and inadequate wash fastness (Pizzicato, 2023; Repon, 2024a; Benli, 2024). Three principal strategies have therefore been investigated:

MORDANTING

Fibre Modification

Process intensification: Mordants can act as intermediaries between colorant molecules and fibres. Metallic ions can coordinate with oxygen-containing functional groups in natural colourants, changing shade and potentially improving fixation. However, the environmental profile of the mordant must be considered. Metallic salts may create additional chemical loads in wastewater and may introduce concerns regarding environmental exposure (Benli, 2024; Repon, 2024b). Fibre modification provides an alternative approach. Surface modification, cationization, enzymes, plasma and crosslinking can alter fibre accessibility or introduce additional binding sites (Thakker, 2022; Shahmoradi Ghaheh, 2021; Cai, 2022; Zhang, 2021). These approaches should not be viewed as mutually exclusive. The most efficient system may combine mild fibre modification with a low concentration of bio-mordant and controlled dye application.

Bio-mordants: Opportunities and Limitations: The search for alternatives to metallic mordants has resulted in growing interest in Bio-mordants. Bio-mordants include tannin-rich plant materials, polysaccharides, proteins and other biological materials capable of enhancing dye–fibre interactions (Benli, 2024; Repon, 2024b). Benli's comprehensive review identifies Bio-mordants as a major research direction in natural textile coloration and discusses their potential as alternatives to conventional metallic mordants (Benli, 2024). Experimental studies have demonstrated the effectiveness of Bio-mordants in cotton and other fibres. Thakker and Sun investigated herbs as both colourants and Bio-mordants for cotton and reported useful colour strength and fastness properties (Thakker, 2022). Rahman *et al*. demonstrated one-bath natural dyeing of cotton using turmeric root extract and chitosan bio-mordant, obtaining improved colour strength and wash fastness (Rahman, 2023). Shahmoradi Ghaheh *et al*. compared metallic mordants and Bio-mordants in terms of colourimetric and antibacterial properties (Shahmoradi Ghaheh, 2021). Agricultural residues can themselves serve as sources of dyes and mordanting materials. Nazir *et al*. demonstrated the use of plant-waste-derived dyes and natural mordants for cotton and reported useful colour strength and fastness properties (Nazir, 2022). Nevertheless, Bio-mordants should not automatically be classified as environmentally superior. Their own extraction, purification, dosage and wastewater characteristics must be included in environmental assessments.

Conventional Exhaust Dyeing versus Resource-Efficient Application:

Conventional exhaust dyeing is widely used because it is technically simple and compatible with small batches. However, it generally requires comparatively large liquor volumes and subsequent washing. Textile wet-processing research has consistently identified water use as a major environmental issue (Hussain, 2018; Khattab, 2020). The challenge is especially relevant to natural dyeing because multiple stages may be involved: scouring, mordanting, dye extraction, dyeing and after-washing.

Ultrasound-assisted dyeing provides one route towards process intensification. Vankar *et al*. demonstrated sonicator-assisted dyeing of cotton with Rubia cordifolia using a bio-mordant (Vankar, 2007), while Zia *et al*. investigated ultrasonic extraction and dyeing using neem bark extract (Zia, 2019). More recent work on Marigold demonstrated that ultrasound-assisted dyeing can reduce water and thermal-energy requirements relative to conventional processing under the investigated conditions (Baig, 2021). The principle is that enhanced mass transfer can improve dye penetration and potentially reduce time or temperature requirements. However, ultrasound systems consume electrical energy. Therefore, the environmental advantage should be determined by using measured energy consumption rather than assuming from reduced processing time.

Padding and Pad-Dry-Steam Processing:

Padding differs fundamentally from exhaust dyeing because dye liquor is mechanically applied to the textile and excess liquor is expressed. This allows controlled wet pick-up and potentially reduces the volume of liquor that must be heated and subsequently discharged. The process becomes particularly interesting when combined with drying and steaming. Pad-dry- steam processing separates liquor application from fixation and provides independent control over application, drying and fixation. Research on pad-steam processing demonstrates the technical feasibility of applying natural dyes to cotton. Khattak *et al*. investigated natural dyes including madder, cutch, marigold and related colourants using a pad-steam process and examined the effects of auxiliaries on fastness (Khattak, 2023). The broader pad-steam literature also demonstrates that controlled steaming can improve fixation and shorten process sequences. Wang *et al*. demonstrated a single-step pad-steam cationization and dyeing process for cotton and reported improved dyeing properties and increased K/S and fixation compared with a conventional process (Wang, 2022). Although that study concerned reactive dyes rather than natural colourants, its process-engineering principles are relevant when developing controlled application systems for natural colourants. The potential advantages for khadi include:

- Controlled liquor application;
- Lower dye-liquor volume;
- Improved shade reproducibility;
- Compatibility with small production lots;
- Potential integration with patterning or sequential coloration; and
- Reduced wastewater volume at the application stage.

Nevertheless, pad-dry-steam should not automatically be described as a “green” technology. Drying and steaming require energy. The environmental balance depends on whether reductions in water and wastewater are sufficient to offset thermal-energy demand.

Colour Strength and Colourimetric Evaluation:

Natural-dyes research requires standardized instrumental colour evaluation. Visual descriptions such as “deep red”, “bright yellow” or “dark blue” are insufficient for scientific comparison. The Kubelka–Munk K/S parameter is widely used as an indicator of apparent colour strength, while CIELAB coordinates provide quantitative information about lightness and chromaticity (Salauddin Sk M., 2021; Repon, 2024a).

The principal parameters are:

L*: lightness;
a*: red–green coordinate;
b*: yellow–blue coordinate;
C*: chroma;
h°: hue angle; and
ΔE: colour difference.

The importance of standardized colour measurement has been emphasized in recent reviews because inconsistent reporting prevents meaningful comparison between natural-dye studies (Salauddin Sk M., 2021; Repon, 2024a). For khadi commercialization, batch-to-batch colour difference is particularly important. Artisanal variation may be desirable within limits, but uncontrolled variation can compromise commercial reproducibility. Natural-dye research should therefore report K/S together with complete CIELAB coordinates, measurement conditions, substrate specifications and process parameters.

Colourfastness and Durability: Colourfastness is a fundamental determinant of the commercial value of dyed textiles. Washing, rubbing and light fastness represent different mechanisms of colour loss and should therefore be evaluated separately. Natural colourants frequently suffer from lower fastness than optimized synthetic dyes, although performance varies considerably among colourant classes and application methods (Pizzicato, 2023; Salauddin Sk M., 2021; Repon, 2024a). Pomegranate-peel dyeing provides a useful example. Otaviano *et al*. demonstrated that pomegranate-peel extract can provide measurable coloration of cotton together with useful fastness and functional properties (Otaviano, 2023). Madder performance can also be improved through fibre modification. Cai *et al*. demonstrated the relevance of crosslinking treatment to the performance of madder-dyed cotton (Cai, 2022). Such findings demonstrate that colourfastness is not solely an intrinsic property of the natural colourant. It is a property of the complete: Dye – fibre – mordant – process system.

Environmental Sustainability: Beyond the "Natural = Green" Assumption: One of the most important conclusions emerging from the literature is that natural dyes cannot automatically be considered environmentally superior to synthetic dyes. Life-cycle assessment of madder dyeing demonstrated that extraction energy and solvent use can become environmental hotspots (Ul-Islam, 2020). Agnhage *et al*. showed that reducing extraction energy and minimizing water use during post-dyeing washing could improve the environmental performance of madder dyeing (Ul-Islam, 2020). This finding has direct implications for khadi. If a natural colourant requires extensive extraction, repeated heating and multiple washing cycles, its environmental advantage may be reduced. Environmental evaluation should therefore include raw material → extraction → mordanting → dye application → drying/steaming → washing → finishing → wastewater → end of life. At minimum, future studies should quantify water consumption, electrical energy, thermal energy, chemical inputs, wastewater volume and residual colourant.

Circular Economy Potential: Agricultural-residue-derived colourants offer an opportunity to combine textile sustainability with biomass valorization. Phan *et al*. highlighted the potential of agro-food residues as sources of valuable natural colourants (Agnhage, 2017). Pomegranate peel, orange peel, sawdust and cork by-products provide examples of residues that have been investigated for textile coloration (Otaviano, 2023; Li, 2022; Coelho Pinheiro, 2023; Chemat, 2017). The circular-economy value is strongest when the colourant source is genuinely a low-value by- product and when the extraction process does not introduce disproportionate environmental burdens. A potential decentralized model for khadi is therefore: local agricultural residue → colourant extraction → khadi coloration → product manufacture → residue recovery. This model may create additional value within rural communities while reducing dependence on dedicated dye crops. However, seasonality, storage stability and compositional variability remain major challenges.

Socioeconomic Role of Sustainable Khadi: The sustainability of khadi extends beyond environmental indicators. Its decentralized production system can support rural livelihoods through spinning, weaving, dyeing, agricultural production and associated activities (Bhalla, 2018). Natural coloration may provide additional economic opportunities by creating differentiated products based on local colourant resources and traditional knowledge. Small-scale production also allows customized shades and limited collections. This flexibility can be advantageous in contemporary markets where product differentiation and craft identity are commercially valuable. However, commercialization requires quality consistency. The challenge is therefore not to eliminate all variation but to establish scientifically defined acceptable ranges of colour and fastness. Technologies such as low-capacity padding, modular steaming and controlled drying may be particularly suitable because they can improve reproducibility without requiring the complete industrialization of the production system.

CRITICAL ASSESSMENT

Currently literature demonstrates substantial progress but also reveals a fragmented research landscape.

i.First, many studies evaluate a single plant material under one set of dyeing conditions. Such studies are useful for screening but provide limited information about scalability.
ii.Second, extraction conditions differ widely among studies. Reporting dye concentration as amass of raw plant material does not necessarily provide comparable colourant concentrations because extraction yield and chemical composition vary.
iii.Third, colourimetric reporting remains inconsistent. Some studies report K/S, others provide only visual descriptions, and relatively few provide complete spectral and CIELAB information (Salauddin Sk M., 2021; Repon, 2024a).
iv.Fourth, fastness testing is inconsistent. Washing, rubbing and light fastness are not always evaluated together.
v.Fifth, sustainability claims are frequently qualitative. A process described as "eco-friendly "should ideally provide measured water and energy consumption.
vi.Sixth, life-cycle assessment remains limited. The madder LCA study demonstrates the importance of considering extraction and washing as environmental hotspots (Ul-Islam, 2020).
vii.Seventh, pilot-scale evidence is limited. Laboratory-scale success does not guarantee uniformity during industrial or cottage-scale production. These limitations demonstrate that the next generation of natural-dye research should shift from dye screening towards integrated process optimization.

Research Gaps and Future Scope: The most important research gaps can be summarized as follows.

- **Standardization of natural colourant feedstocks:** Botanical identity alone is insufficient. Chemical fingerprinting should be incorporated to characterize batch-to-batch variability.
- **Standardized extraction:** Extraction yield, total chromophore concentration and process energy should be reported together.
- **Standardized colour measurement:** Future studies should report K/S, L*, a*, b*, C*, h° and ΔE wherever appropriate (Salauddin Sk M., 2021; Repon, 2024a).
- **Comprehensive fastness assessment:** Washing, rubbing and light fastness should be evaluated using standardized procedures.
- **Optimization of pad-dry-steam:** Systematic studies should investigate wet pick-up, dye concentration, number of padding passes, drying conditions and steaming conditions.

- **Quantitative water and energy balances:** Water should be reported as L kg^{-1} fabric and energy as MJ kg^{-1} fabric wherever possible.
- **Life-cycle assessment:** Future studies should compare natural-dye and conventional-dye routes using consistent system boundaries and functional units.
- **Techno-economic analysis:** Costs should include colourant preparation, labor, energy, water, equipment, wastewater management and quality control.
- **Pilot-scale validation:** Laboratory results should be validated under realistic production conditions.
- **Advanced colour development:** Sequential dyeing, combined natural colourants, overprinting and bio-mordant combinations may broaden the colour palette available to khadi.

Proposed Research Framework: A scientifically robust pathway for future sustainable khadi coloration can be expressed as: Natural biomass ↓ Chemical characterization ↓ Green extraction ↓ Fibre preparation ↓ Biomordant / surface modification ↓ Controlled padding ↓ Drying ↓ Steaming / fixation ↓ K/S + CIELAB + ΔE ↓ Washing + rubbing + light fastness ↓ Water + energy + wastewater assessment ↓ Life-cycle assessment ↓ Techno-economic assessment ↓ Pilot-scale validation ↓ Rural-scale commercialization. Central principle is that no single parameter should be optimized independently. Maximum K/S, for example, should not be pursued at the expense of excessive dye concentration, energy or water consumption. The desired outcome is therefore an optimized sustainability–performance envelope rather than maximum colour depth. Natural colouration represents a promising pathway for strengthening the environmental, cultural and economic identity of khadi cotton. However, the evidence reviewed in this study indicates that the sustainability of natural dyes cannot be inferred solely from their biological origin. The technological performance of natural colourants depends on chemical composition, extraction, fibre preparation, mordanting, application technology and fixation. Indigo, madder, pomegranate peel and other plant-derived colourants demonstrate that a diverse palette of natural shades can be obtained on textile substrates, while Bio-mordants and fibre-modification technologies offer opportunities to improve fixation and durability (Benli, 2024; Otaviano, 2023; Thakker, 2022; Rahman, 2023; Shahmoradi Ghaheh, 2021; Nazir, 2022; Cai, 2022).

Agricultural and industrial residues provide an especially important opportunity because they can connect textile coloration with circular-economy strategies. Pomegranate peel, orange peel, sawdust and cork-processing residues demonstrate that waste streams can serve as sources of textile colourants (Otaviano, 2023; Li, 2022; Agnhage, 2017; Coelho Pinheiro, 2023; Chemat, 2017). Pad-dry-steam processing is particularly promising for khadi because controlled liquor application may reduce the volume of dye liquor and improve shade reproducibility. Nevertheless, its environmental performance cannot be established without considering the energy requirements associated with drying and steaming. Therefore, future research should measure both water and energy rather than relying on qualitative descriptions of “green” processing. Colour science must also become a central component of natural-dye research. K/S, CIELAB coordinates, ΔE and standardized washing, rubbing and light-fastness measurements should be routinely reported (Salauddin Sk M., 2021; Repon, 2024a; Otaviano, 2023). Such data will enable researchers to compare colourants and processing systems objectively and will facilitate the development of commercial shade standards. The most significant future opportunity lies in integrating traditional khadi production with modern process engineering. Local biomass resources, Bio-mordants, controlled padding, low-energy fixation, standardized colour measurement and life-cycle assessment can together provide a pathway towards scientifically controlled sustainable coloration without eliminating the artisanal character of khadi. Ultimately, the scientific advancement of natural-dyed khadi should not be judged by the simple replacement of synthetic dyes with natural materials. Its success should instead be evaluated through an integrated framework in which colour performance, durability, resource efficiency, environmental impact, economic feasibility and social value are optimized simultaneously. Such an approach can transform natural coloration from a predominantly artisanal practice into a scientifically controlled and commercially credible component of sustainable textile production.

Recommendations

1.Standardize natural-colourant feedstocks through botanical authentication and chemical fingerprinting so that batch-to-batch variability can be quantified.
2.Report extraction yield, chromophore concentration, water use and process energy together, rather than evaluating extraction efficiency from yield alone.
3.Establish common colour-reporting protocols using K/S, L*, a*, b*, C*, h° and ΔE, together with measurement conditions, fabric specifications and process parameters.
4.Apply standardized washing, rubbing and light-fastness methods and report all relevant durability results for meaningful comparison.
5.Optimize pad-dry-steam processing through systematic study of wet pick-up, dye concentration, padding passes, drying and steaming conditions, while measuring thermal-energy demand.
6.Quantify water, electrical energy, thermal energy, chemical inputs and wastewater using comparable functional units such as L kg^{-1} fabric and MJ kg^{-1} fabric.
7.Integrate life-cycle assessment and techno-economic analysis into pilot-scale studies, covering colourant preparation, labor, water, energy, equipment, wastewater management and quality control.
8.Validate laboratory findings under realistic decentralized and cottage-scale production conditions before making industrial-scale sustainability claims.
9.Prioritize locally available agricultural and food-processing residues where their collection and extraction do not create disproportionate additional environmental burdens.
10.Preserve the artisanal character and cultural identity of khadi while introducing appropriate scientific controls for colour reproducibility, resource efficiency and product quality.

CONCLUSIONS

Natural colouration represents a promising pathway for strengthening the environmental, cultural and economic identity of khadi cotton. However, the evidence reviewed in this study indicates that the sustainability of natural dyes cannot be inferred solely from their biological origin. The technological performance of natural colourants depends on chemical composition, extraction, fibre preparation, mordanting, application technology and fixation. Indigo, madder, pomegranate peel and other plant-derived colourants demonstrate that a diverse palette of natural shades can be obtained on textile substrates, while Bio-mordants and fibre-modification technologies offer opportunities to improve fixation and durability. Agricultural and industrial residues provide an especially important opportunity because they can connect textile coloration with circular-economy strategies. Pomegranate peel, orange peel, sawdust and cork-processing residues demonstrate that waste streams can serve as sources of textile colourants. Pad-dry-steam processing is particularly promising for khadi because controlled liquor application may reduce the volume of dye liquor and improve shade reproducibility. Nevertheless, its environmental performance cannot be established without considering the energy requirements associated with drying and steaming. Therefore, future research should measure both water and energy rather than relying on qualitative descriptions of “green” processing. Colour science must also become a central component of natural-dye research. K/S, CIELAB coordinates, ΔE and standardized washing, rubbing and light-fastness measurements should be routinely reported. Such data will enable researchers to compare colourants and processing systems objectively and will facilitate the development of commercial shade standards. The most significant future opportunity lies in integrating traditional khadi production with modern process engineering. Local biomass resources, Bio-mordants,

controlled padding, low-energy fixation, standardized colour measurement and life-cycle assessment can together provide a pathway towards scientifically controlled sustainable coloration without eliminating the artisanal character of khadi. Ultimately, the scientific advancement of natural-dyed khadi should not be judged by the simple replacement of synthetic dyes with natural materials. Its success should instead be evaluated through an integrated framework in which colour performance, durability, resource efficiency, environmental impact, economic feasibility and social value are optimized simultaneously. Such an approach can transform natural coloration from a predominantly artisanal practice into a scientifically controlled and commercially credible component of sustainable textile production.

Author Biographies

Natarajan Arunraaj[1] is a Senior Textile Technologist, Sustainable Materials Research Scientist and Ph.D. Research Scholar in the Department of Textile Technology, PSG College of Technology, Coimbatore, India. He is the Chief Executive Officer of Kirish Inc., recipient of the Global Sustainability Award – 2026, and a Sustainability Ambassador since 2024, representing India and the UK for 2025–2026.

With over 29 years of professional experience in textile manufacturing, industrial research and development, technical management and higher education, his expertise encompasses sustainable natural fibres, functional materials, plasma sterilisation, nanoparticle synthesis, natural colouration, circular textiles and industrial sustainability. His doctoral research focuses on the extraction and characterisation of Hibiscus rosa-sinensis fibres for sustainable textile applications. He is also involved in the Water Hyacinth – Fibre to Fabric initiative as Honorary Advisor to the Future Kerala Mission.

His research focuses on valorising underutilised natural resources through innovative fibre development, sustainable processing, waste-to-value pathways and circular product innovation. In this review, he contributes to the critical evaluation of natural colourants, Bio-mordants, resource-efficient colouration technologies and their sustainability implications for khadi cotton, emphasising resource conservation and circularity across the textile value chain.

Dr. P. Senthilkumar[2]***. (Pandurangan Senthilkumar)*** is a Professor (Career Advancement Scheme – CAS) in the Department of Textile Technology (Grant-in-Aid), PSG College of Technology, Coimbatore, India. His academic and research ability encompasses clothing science and comfort, textile and apparel product engineering, plasma-assisted surface modification, functional and medical textiles, sports textiles and sustainable textile processing.

His research contributions focus on the development and performance evaluation of functional textile materials, clothing comfort, thermo-physiological properties, moisture-management fabrics, advanced textile surface treatments and innovative apparel engineering. He has published research articles in reputed international journals, including The Journal of The Textile Institute, Journal of Industrial Textiles, Fibres and Polymers and the Journal of the Textile Association.

His research interests extend to plasma and nanotechnology-based textile modifications, antibacterial functionality, surface wettability, functional material development and sustainable natural fibre applications. As a co-author of this review, he contributes academic and technical ability to the evaluation of natural colouration technologies, dye–fibre interactions, textile processing performance and sustainability considerations for cotton and khadi textiles. His contribution integrates textile science, advanced processing technologies and sustainable material innovation.

REFERENCES

- Agnhage T, Perwuelz A, Behary N. 2017. Towards sustainable Rubia tinctorum L. dyeing of woven fabric: how life cycle assessment can contribute. *Journal of Cleaner Production*. 141:1221–1230. doi:10.1016/j.jclepro.2016.09.183.
- Ajmal M, Adeel S, Azeem M, Zuber M, Akhtar N, Iqbal N. 2014. Modulation of pomegranate peel colourant characteristics for textile dyeing using high energy radiation. *Industrial Crops and Products*. 58:188–193. doi:10.1016/j.indcrop. 2014.04.026.
- Arivithamani N, Dev VRG. 2017. Sustainable bulk scale cationization of cotton hosiery fabrics for salt-free reactive dyeing process. *Journal of Cleaner Production*.149:1188–1199. doi:10.1016/ j.jclepro.2017.02.162.
- Baig U, Khatri A, Ali S, *et al*. 2021. Ultrasound-assisted dyeing of cotton fabric with natural dye extracted from marigold flowers. *Journal of the Textile Institute*. 112:801–808. doi:10.1080/ 004 05000. 2020.1779907.
- Benli H. 2024. Bio-mordants: a review. Environmental Science and Pollution Research.31:20714–20771. doi:10.1007/s11356-024-32174-8.
- Bhalla K, Kumar T, Rangaswamy J. 2018. An integrated rural development model based on comprehensive life-cycle assessment of khadi-handloom industry in rural India. Procedia CIRP.69:493–498. doi:10.1016/j.procir.2017. 11.072.
- Bosiljkov T, Dujmić F, Bubalo MC, Hribar J, Vidrih R, Brnčić M, *et al*. 2017. Natural deep eutectic solvents as a green approach for extraction of bioactive compounds. Food and Bioproducts Processing.
- Cai X, Li H, Zhang L, Yan J. 2022. Ethylene glycol diglycidyl ether applied to crosslinking dyeing of cotton fabric with madder dye. Coloration Technology.138:342–354. doi:10.1111/cote.12593.
- Chemat F, Rombaut N, Sicaire AG, Meullemiestre A, Fabiano-Tixier AS, Abert-Vian M. 2017. Ultrasound assisted extraction of food and natural products: mechanisms, techniques, combinations, protocols and applications—a review. *Ultrasonics Sonochemistry*. .34:540–560.
- Coelho Pinheiro MN, Symochko L, Castro LM. 2023. Valorization of cork industry by-products as sustainable natural dyes for textiles. ACS Sustainable Chemistry & Engineering.11:10555–10565. doi:10.1021/acssuschemeng.3c02576.
- Fu S, Hinks D, Hauser P, Ankeny M. 2013. High efficiency ultra-deep dyeing of cotton via mercerization and cationization. Cellulose. 20:3101–3110. doi:10.1007/s10570-013-0081-6.
- Haji A, Naebe M. 2020. Cleaner dyeing of textiles using plasma treatment and natural dyes: a review. *Journal of Cleaner Production*. 265:121866. doi:10.1016/j.jclepro.2020.121866.
- Hosen MD, Rabbi MF, Raihan MA, Al Mamun MA. 2021. Effect of turmeric dye and Bio-mordants on knitted cotton fabric coloration: a promising alternative to metallic mordanting. *Cleaner Engineering and Technology.* .3:100124.
- Hussain T, Wahab A. 2018. A critical review of the current water conservation practices in textile wet processing. Journal of Cleaner Production. .198:806–819. doi:10.1016/ j.jclepro. 2018. 07.051.
- Kandasamy N, Kaliappan K, Palanisamy T. 2021. Upcycling sawdust into colorant: ecofriendly natural dyeing of fabrics with ultrasound assisted dye extract of Pterocarpus indicus Willd. *Industrial Crops and Products*.171:113969.
- doi:10.1016/ j.indcrop.2021.113969.
- Khattab TA, Abdelrahman MS, Rehan M. Textile dyeing industry: environmental impacts and remediation. Environmental Science and Pollution Research. (2020).27:3803–3818. doi:10.1007/ s11356-019-07137-z.
- Khattak SP, Rafique S, Inayat F, Seemi I. 2023. The role of various dyeing auxiliaries in the fastness characteristics of cotton coloured with various natural dyes through pad-steam

method (Part-I). GUMAN. 6:518–531. doi:10.63075/guman.v6i4.648.

- Li K, Ding Q, Zhang H. 2022. Eco-friendly dyeing of cotton fabric using natural dye from orange peel. Journal of the Textile Institute.113:360–366. doi:10.1080/00405000.2021.1881226.
- Ma X, Wei Y, Wang S, Zuo X, Shen B. 2020. Sustainable ultrasound-assisted ultralow liquor ratio dyeing of cotton fabric with natural turmeric dye. *Textile Research Journal*. .90:685–694. doi:10.1177/0040517519878793.
- Mansour R. 2018. Natural dyes and pigments: extraction and applications. In: Yusuf M, editor. Handbook of Renewable Materials for Coloration and Finishing. Wiley.
- Montazer M, Malek R, Rahimi A. 2007. Salt free reactive dyeing of cationized cotton. Fibres and Polymers.8:608–612. doi:10.1007/BF02875997.
- Nazir F, Siddique A, Nazir A, Javed S, Hussain T, Abid S. 2022. Eco-friendly dyeing of cotton using waste-derived natural dyes and mordants. *Coloration Technology*. .138:684–692. doi:10.1111 /cote.12629.
- Otaviano BTH, Sannomiya M, de Queiroz RS, Ceron A, Freeman HS, Mendoza LER, *et al*. 2023. Natural dye extracted from pomegranate peel: physicochemical characterization, dyeing of cotton fabric, color fastness, and photoprotective properties. Fibres and Polymers. 24:1321–1332. doi:10.1007/s12221-023-00138-3.
- Phan K, Raes K, Van Speybroeck V, Roosen M, De Clerck K, De Meester S. 2021. Non-food applications of natural dyes extracted from agro-food residues: a critical review. *Journal of Cleaner Production*. 301:126920. doi:10.1016/j.jclepro. 2021.126920.
- Phan K, Van den Broeck E, Van Speybroeck V, De Clerck K, Raes K, De Meester S. 2020. The potential of anthocyanins from blueberries as a natural dye for cotton: a combined experimental and theoretical study. Dyes and Pigments. 176:108180. doi:10.1016/j.dyepig.2019.108180.
- Pizzicato B, Pacifico S, Cayuela D, Mijas G, Riba-Moliner M. 2023. Advancements in sustainable natural dyes for textile applications: a review. Molecules.28:5954. doi:10.3390/ molecules28165954.
- Rahman MM, Kim M, Youm K, Kumar S, Koh J, Hong KH. 2023. Sustainable one-bath natural dyeing of cotton fabric using turmeric root extract and chitosan biomordant. *Journal of Cleaner Production.* 382:135303. doi:10.1016/j.jclepro. 2022.135303.
- Repon MR, Dev B, Rahman MA, Jurkonienė S, Haji A, Alim MA, *et al*. 2024. Textile dyeing using natural mordants and dyes: a review. Environmental Chemistry Letters.22:1473–1520. doi:10.1007/s10311-024-01716-4.
- Repon MR, Islam T, Paul TK, Jurkonienė S, Haji A, Shukhratov S, *et al*. 2024. Natural dyes in textile printing: parameters, methods, and performance. *Environmental Science and Pollution Research*.31:47552–47583. doi:10.1007/s11356-024-34424-1.
- Salauddin Sk M, Mia R, Haque MA, Shamim AM. 2021. Review on extraction and application of natural dyes. Textile & Leather Review. 4:218–233.
- Shahmoradi Ghaheh F, Moghaddam MK, Tehrani M. Comparison of the effect of metal mordants and bio-mordants on the colorimetric and antibacterial properties of natural dyes on cotton fabric. Coloration Technology. (2021).137:689–698.
- Thakker AM, Sun D. 2022. Sustainable application of novel herbs on cotton fabrics as Bio-mordants and colourants. *Environmental Science and Pollution Research*. 29:47598–47616. doi:10.1007/s11356-022-18818-7.
- Thakur R, Gupta V, Dhar P, Deka SC, Das AB. 2022. Ultrasound-assisted extraction of anthocyanin from black rice bran using natural deep eutectic solvents: optimization, diffusivity, and stability. *Journal of Food Processing and Preservation*. doi:10.1111/jfpp.16309.
- Uddin MA, Rahman MM, Haque ANMA, Smriti SA, Datta E, Farzana N, *et al*. 2022. Textile colouration with natural colourants: a review. *Journal of Cleaner Production*. 349:131489. doi:10.1016/j.jclepro.2022.131489.
- Ul-Islam S, Butola BS. 2020. A synergistic combination of shrimp shell derived chitosan polysaccharide with Citrus sinensis peel extract for the development of colourful and bioactive cellulosic textile. *International Journal of Biological Macromolecules*.158:94–103.
- Vankar PS, Shanker R, Mahanta D, Tiwari SC. 2008. Ecofriendly sonicator dyeing of cotton with Rubia cordifolia using biomordant. Dyes and Pigments.76:207–212. doi:10.1016/ j.dyepig. 2006.08.023.
- Vankar PS, Shanker R, Verma A. 2007. Enzymatic natural dyeing of cotton and silk fabrics without metal mordants. Journal of Cleaner Production. .15:1441–1450. doi:10.1016/j.jclepro. 2006.05.004.
- Vankar PS. 2000. Chemistry of natural dyes. Resonance.5:73–80.
- Wang L, Xie G, Mi X, Kang X, Zhu Q, Yu Z. 2022.A single-step pad-steam cationisation and dyeing process for improving dyeing properties of cotton fabrics. Coloration Technology. (2022).138:509–521. doi:10.1111/cote.12608.
- Yameen M, Adeel S, Nasreen H, *et al*. 2022. Sustainable eco-friendly extraction of yellow natural dye from Nyctanthes arbor-tristis for coloration of cotton fabric. Environmental Science and Pollution Research. 29:83810–83823. doi:10.1007/s11356-022-21450-0.
- Zhang T, Zhang S, Qian W, He J, Dong X. 2021. Reactive dyeing of cationized cotton fabric: the effect of cationization level. ACS *Sustainable Chemistry & Engineering*. .9:12355–12364. doi:10.1021/acssuschemeng.1c04340.
- Zhang Y, Rather LJ, Li Q. 2022. Recent advances in surface modification strategies to improve functional finishing of cotton with natural colourants: a review. *Journal of Cleaner Production*.335:130313. doi:10.1016/j.jclepro.2021.130313.
- Zia KM, Adeel S, Rehman FU, Aslam H, Khosa MK, Zuber M. 2019. Influence of ultrasonic radiation on extraction and green dyeing of mordanted cotton using neem bark extract. *Journal of Industrial and Engineering Chemistry*. .77:317–322. doi:10.1016/j.jiec.2019.04.054.

****