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Original Article

Sustainable Use of Natural Dyes for Khadi Cotton: A Study on Dye Extraction and Application Techniques

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Abstract

Khadi cotton occupies a unique space within India's contemporary textile landscape as a hand-spun, hand-woven fabric rooted in Gandhian philosophy and rural livelihoods. For khadi to remain relevant in a sustainability-conscious era, its wet processing must align with low-toxicity and resource-efficient principles. This paper examines the sustainable use of natural dyes for khadi cotton with a specific focus on dye extraction and application techniques. Plant-based dyes sourced from babul bark, Butea monosperma petals, marigold flowers, onion peel, pomegranate rind, indigo and madder are reviewed in terms of extraction media, time–temperature combinations, mordant systems and resulting fastness behavior. Drawing upon experimental and review studies, the paper synthesises aqueous decoction, long cold steeping, alkaline extraction and vat dyeing routes for application on khadi cotton. It then discusses how optimised material-to-liquor ratios, pH control, bio-mordants and pad–dry–steam methods can deliver acceptable wash, rub and perspiration fastness for artisanal production scales. Simple bar and pie charts are used to visualize typical fastness grades; distribution of plant parts used as dye sources and indicative water-use reductions compared with conventional reactive dyeing. The study argues that when supported by structured training, cluster-level infrastructure and enabling policies, natural dyeing can strengthen both the ecological credentials and cultural identity of khadi cotton.

Keywords: *Natural dyes; khadi cotton; dye extraction; mordants; sustainable textiles; colour fastness.*

Introduction

Khadi cotton, produced through manual spinning and weaving, emerged historically as a political and ethical response to industrial textiles and colonial trade. Today, it is increasingly promoted as a sustainable textile because it relies on low-capital equipment, decentralised production and relatively low energy inputs. However, the environmental profile of khadi does not depend solely on yarn and fabric formation; colouration and finishing processes have a substantial influence on water, chemical and energy footprints. In many khadi clusters, synthetic dyes such as reactive, direct and naphthol dyes are widely used due to their availability, bright shades and established recipes supplied by chemical traders. These advantages, however, come with environmental costs: high salt usage, unfixed dyes in effluents and exposure of workers to strong alkalis and auxiliary chemicals. In parallel, there is a growing global interest in natural dyes derived from renewable resources. Many of these resources are already familiar to Indian dyers babul bark, myrobalan, pomegranate rind, indigo and madder have long histories in regional craft traditions. What has changed is the framing: natural dyes are no longer discussed only as heritage practices but increasingly as components of sustainable value chains. Khadi cotton, characterised by small batch sizes and flexible production, is particularly suited to such value chains because the slower pace and artisanal processes allow dyers to work with more complex but eco-friendly recipes.

Despite renewed interest, systematic documentation and standardisation of natural-dye processes for khadi remain limited. Much of the existing knowledge exists either as scattered scientific case studies on cotton fabrics or as tacit knowledge held by individual master dyers. This paper therefore attempts to bridge the gap between craft and science. It reviews relevant literature on natural dyes for cotton, highlights specific studies on khadi, and organises practical information on extraction and application techniques into a framework that khadi institutions, training centers and artisan clusters can adapt.

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In doing so, it positions natural dyeing not as a romantic return to the past but as a viable, technically informed pathway for future-oriented sustainable khadi.

Review Of Literature

The literature on natural dyes for cellulosic fibers has grown significantly over the last two decades, reflecting broader concerns about environmental and occupational health. Samanta and Agarwal provided a widely cited overview of natural dye sources and application methods, demonstrating that cotton fabrics can achieve wash fastness grades around 3–4 on the standard grey scale when appropriate mordants and optimised dyeing conditions are used. Their work emphasised that dye extraction method, pH, time, temperature and material-to-liquor ratio are interdependent variables that must be tuned for each dye source.

Saxena and Raja examined the chemistry of important natural dye classes such as flavonoids, anthraquinones and indigoids in the context of sustainability. They argued that natural dyes are most effective when integrated with bio-mordants derived from tannin-rich plant materials like myrobalan, pomegranate rind and sumac, thereby reducing dependence on alum and other metal salts. Their analysis highlighted that although natural dyes may exhibit lower tinctorial strength than synthetic dyes, their overall ecological profile is favourable when biomass wastes are utilised.

More specific to khadi, Tiwari and Srivastava explored eco-friendly printing on cotton khadi fabric using extracts of Butea monosperma petals, eucalyptus leaves and madder roots in combination with myrobalan and alum mordants. They documented the influence of extraction duration and dye concentration on colour yield, and reported moderate to good rubbing and washing fastness for printed motifs. Sinnur and co-authors conducted a detailed experimental standardization of dyeing process variables for cotton khadi using aqueous extracts of babul bark (Acacia nilotica). By systematically varying pH, dye concentration, salt levels and material-to-liquor ratio, they identified optimum conditions around pH 5 and 30 % dye on the weight of fabric, resulting in improved colour strength and satisfactory fastness.

Handique and colleagues investigated pomegranate rind extracts on cotton fabric and elaborated process flow charts covering scouring, bleaching, alkaline extraction of the rind, mordanting using alum and natural tannins, followed by dyeing and washing. Their findings indicated fair to good ratings for washing, rubbing and perspiration fastness, with minimal staining on adjacent fabrics when recipes were carefully balanced. Research on indigo, though often focused on denim and yarn-dyed cotton, is also relevant: studies consistently show that reduced indigo applied in alkaline vats delivers excellent wash and light fastness after oxidation, provided that vat maintenance is carefully controlled.Across these studies, a consistent message emerges: natural dyes can deliver acceptable performance on cotton, including khadi, when scientific process optimisation is combined with traditional knowledge. The literature also flags critical gaps, particularly in the documentation of shade reproducibility under decentralised conditions and in the integration of life-cycle thinking into natural-dye evaluations. This paper builds on the available evidence while addressing these gaps through a khadi-focused process perspective.

Objectives Of the Study

- Based on the literature review and field realities of khadi production, the present study pursues the following objectives: To map key natural dye sources that are locally available and suitable for khadi cotton.
- To compare major dye extraction techniques—aqueous decoction, long cold steeping, alkaline extraction and vat dyeing in terms of practicality and sustainability for khadi clusters.
- To outline application techniques, including mordanting routes and pad–dry–steam methods, that can yield acceptable colour fastness on khadi cotton.
- To highlight ecological and health co-benefits of shifting from synthetic to natural dyes in khadi wet processing.
- To provide visual summaries and practical recommendations that can be used by khadi institutions and training centres as learning and planning tools.

Methodology: Dye Extraction and Application Techniques

Although the present paper is largely analytical and review-based, it is grounded in practical process sequences that have been validated by earlier experimental work on cotton and khadi fabrics. For clarity, the methodology is discussed under two linked components: dye extraction and dye application.

Dye extraction techniques for khadi-compatible natural dyes mostly fall into four categories. First, simple aqueous decoction involves boiling or simmering plant material such as babul bark chips, marigold petals or onion peels in water for 45–90 minutes at temperatures approaching 90 °C. This method is suitable for tannin- and flavonoid-rich dyes and is easy to adopt in village-level dye kitchens. Second, long cold steeping is used where colourants are sensitive to prolonged heating or where energy availability is limited. In this method, finely cut petals or barks are soaked in water at room temperature for up to 48 hours, occasionally stirred, and then filtered to obtain a dye liquor. Third, alkaline extraction is applied particularly to pomegranate rind and certain other fruit peels. Mild alkalinity enhances pigment solubility; processes typically use small amounts of soda ash or lime, keeping pH in a controlled range. Fourth, vat dyeing methods are used for indigo. Here, leaves or prepared indigo cakes are fermented or chemically reduced to produce a soluble leuco form in an alkaline medium.

Application techniques begin with careful fabric preparation. Khadi cotton requires thorough scouring to remove natural waxes, pith and residual sizing materials. Eco-friendly scouring recipes based on non-ionic detergents and limited alkali can be employed at the cluster level. Mordanting is then carried out using either metal saltsmost commonly alum and, in restricted amounts, ironor bio-mordants such as myrobalan, pomegranate rind powder, amla and catechu. Pre-mordanting, where the fabric is

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treated with the mordant before dying, is widely used for tannin-based dyes. Meta-mordanting (mordant in the dye bath) and post-mordanting (after dyeing) are also practised to adjust shade and fastness.

For small-batch khadi dyeing, two main application methods are relevant. Exhaust dyeing in open vessels allows dyers to work with simple equipment, adjusting pH and temperature by experience and with basic instruments. Pad–dry–steam techniques, adapted from industrial practice, involve passing the fabric through a dye liquor (padding), squeezing to a controlled pickup, drying and then steaming to fix the dye. Studies on madder, indigo and pomegranate peel on khadi have shown that pad–dry–steam methods can increase colour strength and improve uniformity compared with purely exhaust methods. In all cases, material-to-liquor ratios between 1:20 and 1:30 and dye-on-fabric concentrations between 15 and 30 % are common starting points, adjusted based on desired shade depth and fabric quality.

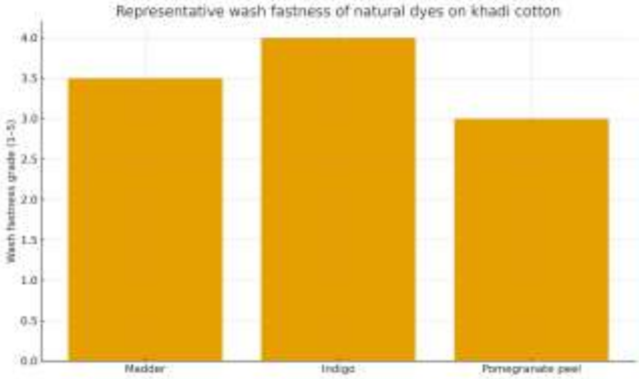
Ecological And Health Co-Benefits

From an ecological perspective, the most significant advantage of natural dyes lies in their potential to reduce toxic chemical loads in effluents. Conventional reactive and direct dyeing of cotton generally involves large quantities of salt, alkali and assorted auxiliaries, of which a considerable fraction remains unfixed and is discharged into wastewater. Colour pollution not only affects the aesthetic quality of water bodies but also impedes photosynthesis and can introduce hazardous intermediates into aquatic ecosystems. By contrast, natural dyes derived from plant materials are largely biodegradable. When agro-residues such as pomegranate peel, onion skin and flower waste are used as feedstock, natural dyeing valorises materials that would otherwise be discarded. Health co-benefits accrue mainly to workers in dyeing units and to consumers with sensitive skin. Dyers working with synthetic dyes often handle strong alkalis, formaldehyde-based resins and, in some cases, aromatic amines without adequate protective equipment. Carefully designed natural-dye processes can operate at milder pH and lower temperatures, reducing the likelihood of chemical burns and inhalation hazards. Consumers increasingly report preferences for garments perceived as 'chemical-free', especially for children's wear, inner garments and yoga or meditation clothing. Naturally dyed khadi cotton, when properly scoured and washed, meets these expectations by minimising residual toxic chemicals in the final fabric. At the same time, it is important to avoid idealised assumptions. Natural dyes are not automatically sustainable; irresponsible harvesting of bark or roots can damage ecosystems, and poorly managed dyeing operations can still waste water. The sustainability advantage emerges when dye plants are cultivated or collected under responsible guidelines, when agro-waste streams are utilised, and when water-efficient, low-chemical processes are implemented alongside basic effluent treatment at the cluster level.

Data Presentation and Discussion

To support training and communication within khadi institutions, complex experimental findings can be translated into simple visual summaries. In this paper, three schematic figures are used for that purpose. The first bar graph compares representative wash fastness grades on khadi cotton dyed with madder, indigo and pomegranate peel using alum-based mordanting. Values around 3.0–4.0 on the five-point grey scale are achievable, with indigo typically performing better because of its vat-dyeing mechanism and strong fibre–dye bonding after oxidation.

The second figure is a pie chart representing the indicative distribution of plant parts used as natural dye sources in the literature surveyed: bark, fruit rinds, flowers, roots and leaves. Bark and fruit residues together account for more than half of reported dye sources, reflecting both their high tannin content and their ready availability as by-products of agriculture and forestry. This distribution has practical implications for khadi clusters seeking to secure reliable raw materials; partnerships with orchards, juice shops, temple flower collection schemes and forestry departments can provide steady supplies of dye raw materials at low cost.The third bar graph presents an indicative water-use index comparing a conventional reactive dyeing route for cotton with an optimised natural-dye process suited to small-batch khadi units. While absolute values vary across studies, the schematic comparison assumes an index of 100 for conventional reactive dyeing and around 65 for the optimised natural-dye route, reflecting reported reductions in rinse cycles, chemical loads and energy consumption. These figures are not presented as precise measurements but as training tools that visually reinforce the potential of process optimisation. Together, the three figures help stakeholders grasp that natural dyeing can offer not only cultural value but also measurable technical and environmental performance.



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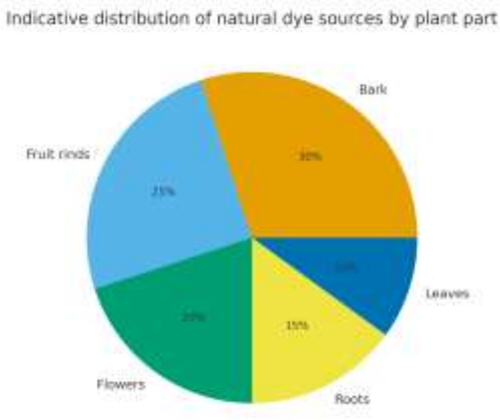

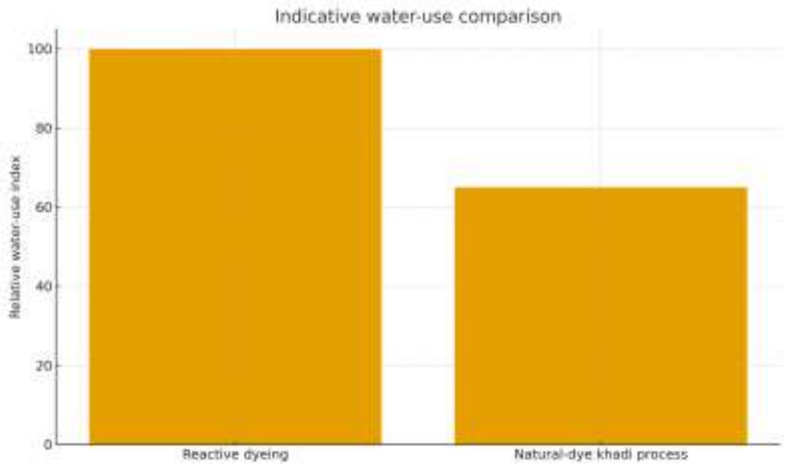

Challenges And Recommendations

Despite promising ecological and cultural advantages, several challenges constrain the widespread adoption of natural dyes for khadi cotton. Raw material variability is a prominent concern: the colour strength of babul bark or pomegranate peel depends on species, growing conditions and storage, leading to shade variation if dyers lack simple quality checks. Establishing village-level or cluster-level standards for moisture content, particle size and minimum tannin levels can greatly improve consistency. Process complexity and skill requirements also present barriers. Compared with packet-based synthetic dyes, natural-dye recipes involve more steps and demand careful control of pH, temperature and time. Many khadi units operate under tight labour and time constraints, making training and visual standard operating procedures essential. The development of simple measuring tools, such as colour comparators and low-cost pH indicators, can support artisans in maintaining process windows. On the economic side, natural dyeing can be cost-competitive when agro-residues and renewable energy sources are used, but initial investments in training, dedicated dye kitchens and effluent treatment facilities may deter small units. Targeted financial support, microcredit and inclusion of naturally dyed khadi in government procurement schemes can improve viability. Marketing and labelling are equally important: clear communication that naturally dyed khadi garments offer both environmental and health benefits can justify modest price premiums and stabilise demand.

Recommendations emerging from this analysis include integrating natural-dye modules into khadi training curricula, setting up cluster-level common facility centres with shared extraction and testing infrastructure, encouraging participatory research linking artisans and academic institutions, and developing simple certification or labelling schemes that highlight natural dye content and responsible sourcing. Together, these measures can transform isolated experiments into a mainstream practice within the khadi sector.

Conclusion

The sustainable use of natural dyes for khadi cotton stands at the intersection of heritage conservation, rural livelihoods and environmental responsibility. By synthesising literature on dye sources, extraction methods, mordanting strategies and application techniques, this paper has outlined how khadi cotton can be coloured using plant-based dyes while achieving acceptable technical performance. Aqueous and alkaline extractions, combined with bio-mordants and either exhaust or pad dry steam application routes, can yield wash fastness grades suitable for apparel and home textiles.

The discussion of ecological and health co-benefits, alongside schematic visualisations of fastness and water use, indicates that natural dyeing has the potential to significantly reduce chemical loads and support circular use of biomass. Yet, realising this potential requires coordinated action across research, training, policy and markets. When khadi institutions, design schools, NGOs and government agencies collaborate to document, standardise and scale natural-dye processes, khadi cotton can evolve into a flagship example of sustainable, culturally rooted textile production. In that sense, natural dyes are not merely a link to the past but an active ingredient in shaping a more responsible textile future.

Annexure: Practical Protocol for Natural Dyeing of Khadi Cotton

For khadi institutions and training centres, a stepwise practical protocol is often more useful than isolated recipes. The following outline summarises a generic procedure that can be adapted for different natural dyes while maintaining the principles discussed in the main text.

Step 1 – Grey fabric inspection and sorting: Khadi cotton should be checked for yarn count, fabric density and visible defects. Lots are sorted so that fabrics of similar construction are processed together, improving shade uniformity. Any visible oil or stain marks are pre-treated with mild detergent.

Step 2 – Eco-friendly scouring: Fabrics are scoured in a bath containing a small dose of non-ionic detergent and limited alkali, at material-to-liquor ratios around 1:30. The temperature is raised gradually to 80–90 °C and maintained for 45–60 minutes, followed by thorough rinsing. Where possible, softened or harvested rainwater is used to reduce hardness-related problems.

Step 3 – Mordanting: Depending on the chosen dye and desired shade, fabrics are pre-mordanted with alum, myrobalan, pomegranate rind extract or combinations thereof. Concentrations in the range of 10–20 % on the weight of fabric are typical. Mordanting is carried out at 60–80 °C with occasional agitation, followed by squeezing and drying in the shade. Step 4 – Dye extraction: Plant material is weighed relative to fabric weight, usually between 50 and 100 % on the weight of fabric. For aqueous decoction, the material is boiled or simmered for 60–90 minutes, then allowed to cool and filtered. For cold steeping, the same ratio is soaked at room temperature for up to 48 hours. In the case of pomegranate rind, mild alkali may be added to aid extraction, while indigo requires preparation of a reduced vat.

Step 5 – Dyeing: Mordanted fabrics are introduced into the dye bath at room temperature, then the temperature is raised to 60–90 °C depending on the dye. Gentle agitation ensures level dyeing. Time in the bath typically ranges from 45 to 60 minutes. For darker shades, a second padding or exhaust cycle can be used. In indigo dyeing, repeated short dips and oxidations in air build up depth.

Step 6 – Washing, soaping and drying: After dyeing, fabrics are rinsed until the rinse water runs nearly clear. A mild soaping step improves wash fastness for many dyes. Final drying is carried out in the shade to minimise photodegradation. Effluents from dyeing and washing are collected for simple treatment settling of solids, pH adjustment and, where possible, use in gardening or non-critical cleaning tasks.

Step 7 – Documentation and evaluation: Each batch is recorded with details of fabric construction, dye source, extraction time, mordant type, bath pH and temperature. Simple visual shade cards and occasional laboratory fastness tests help build a local knowledge base. Over time, this protocol-based approach enables khadi clusters to refine their own standard operating procedures while retaining flexibility for creative experimentation.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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