

Environmental Sustainability through Indigenous Natural Dyeing Practices: A Case Study of Kotpad Handloom Traditions of Odisha, India

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ABSTRACT

Sustainability in textile production is a critical global environmental concern. Some of the major impacts include the ecological burden of synthetic dyes, chemical effluents, high water consumption, and high energy-intensive processes. In such a state, traditional natural dyeing practices, rooted in local ecology and indigenous knowledge systems, offer viable alternatives due to their circular use of resources. This paper examines the environmental sustainability of Kotpad handloom textiles from the Koraput district of Odisha, India, focusing on the natural dyeing of cotton yarn using Aal root bark (*Morinda citrifolia*). Practiced by the Mirigan weaving community, Aal dyeing is a bio-based, low-chemical, resource-sensitive process. The study draws on primary data collected through semi-structured interviews with artisans and master weavers in Kotpad, as well as secondary data from published research and institutional sources. It examines the use of local resources—Aal root bark, castor oil, cow dung, wood ash, river water, sunlight, and iron waste—across the full dyeing cycle. Eco-friendly processes analyzed include fermentation-assisted dye extraction, alkaline scouring with bio-based inputs, aqueous extraction, repeated dyeing cycles to increase color depth, and iron mordanting using recycled metallic waste. A comparative analysis of water consumption, energy use, carbon emissions, and effluent toxicity demonstrating the environmental advantages of Kotpad dyeing over conventional synthetic processes has also been included. Quantitative data and process documentation have been presented in tabular form to support the analysis. The paper concludes that Kotpad's Aal-dyed handloom tradition is a model of circular, low-carbon textile production and discusses its potential for integration into sustainable textile policy and modern eco-fashion systems.

Keywords:

Environmental sustainability, Kotpad handloom, *Morinda citrifolia*, eco-friendly textile process, sustainable fashion, circular economy.

INTRODUCTION

The textile and apparel industry is one of the most resource-intensive sectors globally, relying heavily on water, chemicals, energy, and synthetic raw materials. The ecological burden of reactive and azo synthetic dyes is well documented: their production involves petrochemical intermediates, and their application generates toxic, often non-biodegradable effluents that contaminate water systems and soil (Brüschweiler & Merlot, 2017). In response to these challenges, there is growing scholarly and policy interest in traditional and indigenous textile practices that offer lower-impact alternatives grounded in ecological knowledge and circular resource use.

This paper examines Kotpad handloom textiles from the Koraput district of Odisha, India, and their distinctive natural dyeing system based on Aal root bark (*Morinda citrifolia*). Practiced by the Mirigan weaving community, Kotpad dyeing integrates plant-based dyes, renewable processing inputs, fermentation techniques, and community-level craft production. The study situates these practices within contemporary frameworks of

environmental sustainability, the circular economy, and slow fashion, and draws on both primary fieldwork and secondary sources to analyse their ecological advantages and limitations.

The research contributes to discussions on sustainable textile systems and the documentation of indigenous knowledge. It addresses a gap in the literature by providing a structured, evidence-based environmental analysis of Kotpad dyeing, supported by comparative data and process documentation. The study also explores how such indigenous systems might be integrated into modern sustainable textile industries and policy frameworks.

OBJECTIVES OF THE STUDY

The major objectives of this paper are:

- To assess the environmental sustainability of Kotpad natural dyeing practices by examining resource use, production processes, and waste generation.
- To identify and evaluate the ecological profile of local resources used in Aal dyeing, including their renewability and circular potential.
- To analyze eco-friendly processes for yarn preparation, dye extraction, mordanting, and weaving, with a focus on minimizing environmental harm.
- To compare the environmental impact of Kotpad textile production with that of conventional synthetic dyeing, using quantitative indicators of water consumption, energy use, and effluent toxicity.
- To explore pathways for integrating Kotpad natural dyeing into contemporary sustainable fashion and circular textile policy frameworks.

METHODOLOGY

This study has adopted a qualitative case study methodology to develop an in-depth understanding of the environmental sustainability of natural dyeing in Kotpad. The case study approach is appropriate for craft-specific, community-based, and ecologically embedded practices where contextual richness and process-level detail are essential (Yin, 2018).

Primary data were collected through semi-structured interviews with eight Mirigan artisan weavers and three master weavers in the Kotpad weaving cluster in Koraput district, Odisha. Interviews were conducted in Odia and translated by the first author. Questions addressed indigenous dyeing knowledge, resource procurement, step-by-step process practices, seasonal dependencies, water and material use, and livelihood dimensions. Field observations were conducted during artisan visits to document the physical dyeing environment, available materials, and production workflow.

Secondary data were drawn from peer-reviewed publications on natural dyeing, anthraquinone chemistry, and sustainable textiles (Jena et al., 2026; Samanta & Singhee, 2023; Li et al., 2022); institutional documentation regarding the Kotpad GI status; and conference proceedings on sustainable textile development (ICASTSD Virtual–2026). Quantitative indicators — including estimated water consumption, energy intensity, and effluent toxicity comparisons — were compiled from published benchmarks in the natural and synthetic dyeing literature (UNEP, 2019; Benli, 2024; Pizzicato et al., 2023) and triangulated with primary observations.

Data analysis followed thematic coding organized into four analytical categories:

- (1) local resource ecology,
- (2) eco-friendly process systems,
- (3) comparative environmental impact, and
- (4) sustainability challenges and future directions.

Findings have been presented with supporting tables and process documentation to enhance analytical transparency and reproducibility.

KOTPAD HANDLOOM AND THE ECOLOGY OF AAL DYEING

Kotpad handloom is closely linked to the forested landscape of Koraput, using Aal root bark as the primary natural dye. Aal (*Morinda citrifolia*) grows naturally in the region's mountain forests, and this intimate connection between craft and landscape is central to the tradition's ecological character. Unlike industrial dye systems that depend on imported petrochemicals, Kotpad textiles reflect the natural environment through both their material inputs and their visual language.

The fabrics are known for their earthy palette of terracotta, red, maroon, brown, and black — colors achieved through slow extraction, repeated dyeing, mordanting, and sun exposure. The extra-weft motifs, including fish, crabs, trees, huts, leaves, and flowers, symbolize the natural world of Koraput, making the craft not merely a use of nature but an expression of ecological belonging. Handloom weaving reduces electricity use and keeps production decentralized and community-centered, supporting rural livelihoods without industrial infrastructure.

The following sections examine the key local resources and eco-friendly processes that constitute the Kotpad natural dyeing system.

LOCAL RESOURCES IN KOTPAD AAL DYEING

Table 1 summarizes each local resource, its ecological role, and its sustainability profile. The following subsections discuss each resource in detail.

Table 1: Local Resources in Kotpad Aal Dyeing — Ecological Role and Sustainability Profile

Resource	Source Type	Ecological Role	Sustainability Consideration
Aal root bark	Plant-based, renewable	Primary dye source; contains anthraquinones (morindone, rubiadin) with coloring and antimicrobial properties	Requires regulated harvesting and community cultivation to prevent depletion of <i>Morinda citrifolia</i>
Castor oil	Plant-derived, biodegradable	Wetting agent for yarn; improves dye penetration in cellulose fibres	Biodegradable; renewable; no synthetic surfactant residues
Cow dung	Animal by-product, bio-scouring agent	Alkaline scouring (pH >7); increases hydrophilicity and mordant absorption of cotton	Zero-cost circular input; replaces synthetic scouring agents; biodegradable
Wood ash water	Domestic by-product, alkaline solution	Pre-treatment alkalinity (pH 9–11); swells cotton fibres; enhances dye fixation	Repurposes waste from domestic hearths; no environmental cost
Iron waste	Recycled metal from ironsmiths	Mordant for brown and black shades; fermented with jaggery and water	Reuses artisan waste; avoids industrial mordants; iron discharge needs monitoring at scale
Sunlight	Renewable solar energy	Drying and photo-oxidative colour development between dyeing cycles	Zero-carbon energy input; central to low-emission production profile
River/well water	Local natural resource	Washing, soaking, dye extraction, rinsing	Requires water use documentation; potential for partial water recycling through sedimentation

5.1 Aal Root Bark (*Morinda citrifolia*)

The most important resource in Kotpad dyeing is the bark of the Aal root, sourced from *Morinda citrifolia*. Aal root extract contains anthraquinone and phenolic compounds, including morindone and rubiadin, which impart red color and antimicrobial activity (Jena et al., 2026; Gulati et al., 2022). This gives Kotpad textiles both aesthetic and functional significance. From an environmental perspective, Aal is a renewable, plant-based dye source. However, sustainability depends on responsible harvesting, community-managed regeneration, and regulated cultivation. Uncontrolled extraction of root bark risks depleting natural Aal stands and damaging forest-floor regeneration. Community nurseries and rotational harvesting protocols are therefore essential for long-term ecological balance.

5.2 Castor Oil

Castor oil is used in yarn preparation. Yarn bundles are dipped in a water-and-castor-oil solution, then manually rubbed and stomped to ensure uniform absorption. Castor oil is plant-derived and biodegradable, serving as a natural wetting and softening agent that reduces surface tension and improves dye penetration into cotton cellulose (Jena et al., 2026). Its use avoids synthetic surfactants, leaving no persistent chemical residues.

5.3 Cow Dung

Cow dung is used as a bio-scouring agent to clean and prepare cotton yarn for dyeing. When applied as a semi-solid slurry and dried in sunlight, it creates a mildly alkaline environment ($\text{pH} > 7$) that increases cotton fiber hydrophilicity, improves mordant absorption, and enhances dye penetration (Jena et al., 2026). As a zero-cost by-product of local animal husbandry, it entirely replaces synthetic scouring agents and is fully biodegradable.

5.4 Wood Ash Water

Wood ash from kitchen hearths is mixed with water and left to stand overnight. The resulting alkaline solution ($\text{pH} 9\text{--}11$) swells cotton fibers, improves dye penetration, and enhances color fixation by increasing the solubility of phenol and anthraquinone compounds (Jena et al., 2026). Wood ash is a by-product of domestic fuel use, and its use in dyeing exemplifies circularity: household waste is converted into a functional input for textile processing at zero cost and without environmental penalty.

5.5 Iron Waste

Iron waste from local ironsmiths serves as a mordant to produce darker shades, such as coffee brown and black. When mixed with water and jaggery and fermented for three to four days, this bio-mediated process yields an iron-rich mordant bath without relying on industrial chemical mordants (Jena et al., 2026). The practice reuses metallic waste from another local occupation, reducing the overall waste burden. However, iron-bearing wastewater should be monitored for localized soil and water contamination if production is scaled.

5.6 Sunlight, Water, and Manual Labor

Sunlight is repeatedly used for drying and photo-oxidative color development between dyeing stages. Water is used for washing, soaking, dye extraction, and final rinsing. Manual labor drives all stages of scouring, stomping, washing, drying, and weaving. The energy profile of Kotpad dyeing is therefore substantially lower than that of mechanized textile production, relying on human skill, solar energy, and household-level processing.

ECO-FRIENDLY PROCESSES IN KOTPAD DYEING

Table 2 documents the complete Aal dyeing process, stage by stage, including materials used, ecological function, and approximate duration. This process flowchart, presented in tabular form, provides systematic visual documentation of the dyeing sequence.

Table 2: Kotpad Aal Dyeing Process — Stage-by-Stage Documentation

Stage	Process Step	Materials Used	Ecological Function	Approx. Duration
1	Yarn scouring with cow dung	Red cow dung, water, sunlight	Alkaline pre-treatment (pH >7); opens cotton fibres; removes impurities without synthetic detergents	1–2 days
2	Alkaline wash with wood ash water	Wood ash (pH 9–11), water	Swells cotton fibres; improves dye penetration; zero-cost circular input from domestic fuel waste	Overnight soak
3	Castor oil treatment	Castor oil, water	Bio-based wetting agent; reduces surface tension; improves uniform dye uptake in cellulose	1 day
4	Aal root bark aqueous extraction	Aal root bark (Morinda citrifolia), river water	Water-based dye extraction; no solvents; releases anthraquinones (morindone, rubiadin) responsible for red colour	3–5 days fermentation
5	Repeated dyeing cycles	Aal dye bath, river water	Deepens colour through layering; improves wash fastness without chemical accelerants; produces terracotta to dark maroon shades	10–15 days (multiple dips)
6	Iron mordanting	Iron waste (from ironsmiths), water, jaggery	Fermented iron mordant (3–4 days); produces coffee brown and black shades; reuses metallic waste; avoids synthetic mordants like alum sulphate	4–5 days (incl. fermentation)
7	Sun drying	Sunlight	Zero-energy drying; also assists photo-oxidative colour development	Daily between steps
8	Final washing and handloom weaving	Water, traditional pit loom	Removes excess dye bath; yarn woven manually — no electricity consumed; decentralised small-batch production	3–5 days
Total approx. duration			Entire cycle: 25–30 days for 4–5 kg cotton yarn batch	25–30 days

6.1 Aqueous Extraction

Kotpad dyeing uses water-based extraction rather than solvent extraction. The entire dye-release process is aqueous and fermentation-assisted, with Aal root bark as the primary dye source (Jena et al., 2026). This is a significant environmental advantage because solvent-based extraction produces toxic residues that require specialized treatment. The exclusive use of water and fermentation in Kotpad eliminates this burden entirely.

6.2 Fermentation-Assisted Dyeing

Fermentation plays a central role in both dye extraction and mordant preparation. It softens plant tissue, releases anthraquinone color compounds, and increases dye availability. Fermentation is also used to prepare the iron mordant by combining iron waste with jaggery and water over three to four days (Jena et al., 2026). This bio-mediated approach replaces harsh chemical accelerants with time and microbial activity, reflecting the ecological intelligence of the tradition.

6.3 Alkali-Assisted Fibre Preparation

Cow dung and wood ash create alkaline conditions that prepare cotton for dye uptake. These mild, locally sourced, biodegradable alkaline inputs increase the solubility of phenolic and anthraquinone compounds, release active dye molecules, and swell cotton cellulose, thereby improving penetration and fixation (Jena et al., 2026). The environmental value lies in avoiding industrial scouring chemicals such as sodium hydroxide or sodium carbonate, which require neutralization before discharge.

6.4 Repeated Dyeing and Slow Colour Development

Kotpad dyeing is not a rapid industrial process. The complete Aal dyeing cycle takes about 25–30 days for a single batch of 4–5 kg of cotton yarn (Jena et al., 2026). Repeated dyeing yields deeper color development and better fixation without chemical accelerants. Although commercially slow, this approach supports durability, craft uniqueness, and reduced chemical load, aligning with slow fashion principles that prioritize value derived from time, skill, longevity, and cultural meaning (Fletcher, 2014).

6.5 Handloom Weaving

Following dyeing, yarn is woven manually on pit looms. Handloom production requires significantly less energy than powerloom or mill-based production. It enables small-batch output, reducing overproduction and inventory waste. Kotpad textiles — sarees, stoles, dupattas, dress material, and home textiles — are designed for longevity and can be repurposed across multiple product categories, extending product life and reducing replacement rates.

ENVIRONMENTAL IMPACT OF KOTPAD TEXTILE PRODUCTION

7.1 Reduced Chemical Load

The most significant environmental benefit of Kotpad dyeing is the near-complete elimination of synthetic chemicals. The process relies exclusively on Aal root bark, castor oil, cow dung, wood ash, and iron waste. Since dye extraction is aqueous and fermentation-assisted, the chemical burden is substantially lower than that of synthetic reactive or azo dyeing, which requires reactive auxiliaries, fixing agents, and salts that contribute to toxic effluent loads (Brüschweiler & Merlot, 2017; Li et al., 2022).

7.2 Biodegradability and Natural Fibre Compatibility

Kotpad textiles are produced on natural cotton, which is biodegradable under appropriate conditions. Natural dyes interact well with natural fibres, and their biodegradable inputs leave no persistent chemical residues in soil or water (Li et al., 2022; Pizzicato et al., 2023). Mordant-containing effluents, particularly from iron waste baths, require monitoring, but they carry significantly lower toxicity than heavy-metal mordants such as chrome or tin used in conventional dyeing.

7.3 Lower Carbon Footprint

Kotpad production relies on manual processes, solar drying, and handloom weaving. This eliminates dependence on electricity-driven machinery, fossil-fuel-powered heating systems, and mechanised drying. While boiling and heating are involved in dye extraction, their contribution to total carbon emissions is minimal relative to large-scale industrial dyeing operations that run continuous mechanical vats, chemical mixing facilities, and drying chambers (UNEP, 2019). The production’s decentralised, home-based structure further reduces transport and infrastructure emissions.

7.4 Circular Use of Local Waste

The use of wood ash and iron waste as functional textile inputs illustrates circularity at the craft level. Domestic hearth ash becomes an alkaline processing agent; iron from blacksmithing becomes a mordant; cow dung becomes a bio-scouring medium. These practices convert local by-products into productive inputs, reducing waste generation and fostering interdependence among local occupations within the Koraput artisan economy.

7.5 Functional Longevity and Antimicrobial Properties

Aal dye offers functional value beyond color. Anthraquinone compounds — particularly morindone and rubiadin — bind to cotton through mordanting and help inhibit microbial growth (Jena et al., 2026; Gulati et al., 2022). Iron ions and bioactive phenolic compounds, including flavonoids and terpenoids, contribute additional antimicrobial effects (Adeel et al., 2023; Alemu Reta et al., 2024). Laboratory studies on related anthraquinone-dyed textiles confirm inhibitory activity against common pathogenic bacteria including *Staphylococcus aureus* and *Escherichia coli* (Gulati et al., 2022; Krishnaraj et al., 2024), suggesting that Kotpad fabrics have potential for healthcare-adjacent and hygiene-sensitive applications without synthetic antimicrobial finishes. Functional longevity is critical for sustainability: textiles that remain useful longer have a lower replacement rate and a smaller cumulative environmental footprint.

COMPARISON WITH CONVENTIONAL TEXTILE DYEING

Table 3 presents a systematic comparative analysis of Kotpad Aal natural dyeing and conventional synthetic dyeing across key environmental parameters. Quantitative benchmarks are drawn from published literature and include estimated figures for water consumption, energy use, and effluent characteristics.

Table 3: Comparative Environmental Analysis — Conventional Synthetic Dyeing vs. Kotpad Aal Natural Dyeing

Parameter	Conventional Synthetic Dyeing	Kotpad Aal Natural Dyeing
Dye source	Petrochemical/synthetic intermediates	Aal root bark (<i>Morinda citrifolia</i>) from local ecology
Extraction method	Chemical-intensive industrial process using solvents and fixatives	Aqueous, fermentation and alkali-assisted extraction
Processing aids	Synthetic auxiliaries, salts, reactive fixing agents	Castor oil, cow dung, wood ash, iron waste
Water consumption (per kg fabric)	~100–200 litres (UNEP, 2019)	~40–60 litres estimated (multiple batch reuse)
Energy use	High — machinery, temperature-controlled vats, mechanical drying	Low — manual processing, solar drying, handloom weaving
CO ₂ emissions (relative)	High: energy-intensive dyeing + chemical synthesis	Low: no fossil fuel machinery; mostly solar and human energy

Parameter	Conventional Synthetic Dyeing	Kotpad Aal Natural Dyeing
Wastewater toxicity	High: reactive dyes, heavy metals, AOX compounds	Low: organic residue; iron-wash water requires monitoring
Effluent treatment required	Yes — mandatory chemical treatment before discharge	Minimal — biodegradable inputs; no industrial effluent plant needed
Production scale	Large-scale, fast, standardised	Small-batch, slow, craft-based (~4–5 kg/25–30 days)
Biodegradability	Low — synthetic dye residues persist in soil and water	High — natural dyes and plant-based inputs are biodegradable
Cultural and ecological value	Usually low or detached from place	Strong link with Koraput, Mirgan/Mirigan community, tribal motifs
Sustainability model	Efficiency-led industrial production	Ecology-led slow and circular production

This comparison demonstrates that Kotpad dyeing is not merely a heritage practice but a viable environmental alternative to industrial textile production. Its strengths lie in low chemical dependency, circular local resource use, low-carbon handloom production, and biodegradable material inputs. Its vulnerabilities — scalability, water management, and raw material pressure — are addressed in the Challenges section below.

CHALLENGES IN ENVIRONMENTAL SUSTAINABILITY

9.1 Pressure on Aal Resources

Since Aal dye is extracted from root bark, unsustainable harvesting practices risk undermining plant regeneration and natural forest cover in Koraput. Community-managed Aal plantations, regulated rotational harvesting, and botanical resource mapping are essential to prevent ecological depletion.

9.2 Water Consumption

Although the dyeing process is chemical-free, it involves multiple washing, soaking, and rinsing cycles. An estimated 40–60 litres of water per kilogram of yarn is used across a full batch (based on field observation and comparison with published natural dyeing benchmarks; Pizzicato et al., 2023). Water use must be systematically documented and improved through low-cost recycling, sedimentation tanks, and responsible disposal methods.

9.3 Mordant Management

Iron waste mordanting is more sustainable than industrial chemical mordants, but excessive discharge of iron-bearing wastewater can affect soil quality and water bodies at scale. Small-scale monitoring, effluent management, and pH testing would strengthen the environmental credibility of the process and support any future eco-certification application.

9.4 Time and Labour Intensity

The 25–30-day production cycle per batch supports quality and ecological integrity but increases labour cost and limits volume. Fair pricing mechanisms, artisan-centred value chains, and premium market positioning are necessary to ensure that slow production remains economically viable for Mirgan/Mirigan weavers.

9.5 Standardisation Without Loss of Craft Identity

Natural dyeing produces inherent shade variation, which is part of Kotpad’s aesthetic identity but can challenge market expectations of colour consistency. Scientific process documentation, shade card development, pH and

mordant ratio recording, and wash-fastness testing can address this without erasing the handmade character of the craft.

DISCUSSION: KOTPAD AS A MODEL OF SUSTAINABLE TEXTILE PRODUCTION

Kotpad natural dyeing demonstrates that environmental sustainability is not a new concept introduced from outside but an intrinsic dimension of certain indigenous production systems. The process reveals a sophisticated understanding of fiber chemistry, plant-based alkalinity, fermentation, mordanting, and color fixation — all achieved without synthetic inputs. The craft's environmental, cultural, and livelihood dimensions are interdependent and mutually reinforcing.

Kotpad textiles hold Geographical Indication (GI) status and are produced through documented natural dye extraction and yarn dyeing processes without synthetic chemicals, supporting their market positioning as eco-certified, functionally validated artisan textiles (Jena et al., 2026). This creates a value proposition for eco-conscious consumers, institutional buyers, and sustainable fashion designers that is grounded in scientific evidence rather than heritage alone.

The Kotpad case also expands the theoretical understanding of the circular economy. In industrial frameworks, circularity is typically operationalized through recycling, waste reduction, and closed-loop material flows. In Kotpad, circularity is cultural and ecological in character: local plant material becomes dye, household ash becomes an alkaline processing agent, iron from blacksmithing becomes a mordant, sunlight becomes production energy, and community craft knowledge becomes production infrastructure. This model is small in scale but powerful in its conceptual contribution to sustainability science.

From a policy perspective, indigenous craft-based dyeing systems such as Kotpad offer important evidence for sustainable textile governance. They demonstrate that pre-industrial knowledge systems can meet contemporary sustainability benchmarks in water efficiency, chemical reduction, carbon footprint, and biodegradability — often surpassing modern industrial standards on multiple dimensions. Integrating such systems into national sustainable textile policies, eco-labeling frameworks, and circular economy roadmaps would not only preserve biodiversity and community knowledge but also create scalable sustainability models for the broader textile sector.

RECOMMENDATIONS

- **Aal Resource Management:** Establish community-managed Aal plantations and regulated harvesting protocols to prevent ecological depletion of *Morinda citrifolia* in Koraput forests.
- **Water Management:** Introduce low-cost water recycling, sedimentation, and reuse systems at the cluster level to reduce per-batch water consumption.
- **Process Documentation:** Prepare standardized scientific process manuals recording pH values, dye concentrations, mordant ratios, temperature ranges, and dyeing duration for each stage.
- **Eco-Certification:** Pursue natural dye, handloom, GI, and eco-textile certification for premium market access, aligning with frameworks such as GOTS, Oeko-Tex, and India's Handloom Mark.
- **Product Diversification:** Develop Kotpad-based sustainable product lines including wellness textiles, maternity and children's wear, home textiles, and hospital-adjacent applications leveraging the antimicrobial properties of Aal dye.
- **Artisan-Centred Value Chains:** Ensure sustainability branding and premium pricing benefit the Mirigan weavers directly through fair trade partnerships and cooperative market structures.
- **Collaborative and Interdisciplinary Research:** Promote partnerships among textile scientists, environmental researchers, designers, and craft communities to advance scientific documentation and market development.

- Life Cycle Assessment: Conduct a full life cycle assessment (LCA) comparing Kotpad natural dyeing with synthetic dyeing to generate robust quantitative data for policy advocacy and eco-labeling applications.

CONCLUSION

Kotpad natural dyeing represents a significant model of environmental sustainability embedded within an indigenous textile tradition. Its use of Aal root bark, castor oil, cow dung, wood ash, iron waste, sunlight, water, and manual skill reveals a production system that is deeply connected to local ecology, shaped by generations of environmental knowledge, and structured around circular resource use. The process avoids solvent extraction, minimizes synthetic chemical dependency, uses biodegradable and locally sourced inputs, repurposes domestic and artisan waste, sustains handloom livelihoods, and produces textiles with documented antimicrobial functionality.

The comparative environmental analysis presented in this paper demonstrates that Kotpad dyeing consistently outperforms conventional synthetic dyeing across water toxicity, carbon emissions, chemical load, and biodegradability, while producing textiles of significant cultural and functional value. These findings support a view of Kotpad not merely as a heritage craft in need of preservation, but as a living, evidence-based sustainability model relevant to contemporary challenges in textile production and consumption.

Sustainability must nonetheless be treated as a dynamic responsibility rather than a fixed heritage claim. Responsible Aal cultivation, careful water management, monitoring of iron mordants, scientific process documentation, and fair artisan value chains are necessary to protect the craft's ecological and social foundations in the long term. The pathway from heritage practice to recognized sustainable system requires not only documentation but institutional support: eco-labeling policies, craft cluster investment, and interdisciplinary research partnerships that bring together textile science, environmental studies, and design.

In the broader context of sustainable development, Kotpad handloom offers a compelling case for integrating indigenous knowledge systems into mainstream sustainable textile policy. It demonstrates that sustainable futures need not depend solely on technological innovation but can also emerge from ecological intelligence, slow craft processes, and respectful relationships among community, material, and environment. The challenge — and the opportunity — lies in creating the institutional conditions that allow such systems to thrive, scale responsibly, and inform the design of more sustainable textile industries worldwide.

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