iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** III **Month of publication:** March 2026

DOI: https://doi.org/10.22214/ijraset.2026.78514

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue III Mar 2026- Available at www.ijraset.com

Sustainable Coloration of Handloom Textiles Using Plant Dyes

Vaishnavi B [1], Dr K M Pachiyappan[2], Nathiya K[3]
[1]PG Student, [2]Associate Professor & Dean, School of Applied Science, [3]PhD Research Scholar Department of Costume Design and Fashion, PSG College of Arts and Science, Coimbatore.

Abstract: ***Plant-based natural dyes are colorants derived from renewable botanical sources such as leaves, roots, bark, flowers, and fruits. They have been used for centuries in textile coloration, particularly in handloom textiles that emphasize sustainability, cultural heritage, and eco-friendly production methods. In recent years, growing environmental concerns regarding synthetic dyes have renewed interest in plant-based dyes due to their biodegradable, non-toxic, and sustainable nature. This article presents a comprehensive overview of plant-based natural dyes, focusing on their characteristics, extraction, applications, and uses in handloom textiles, along with recent advancements and challenges in their adoption.***
Keywords: biodegradable, non-toxic, cultural heritage, sustainable nature and eco-friendly

I. INTRODUCTION

The global textile industry has increasingly shifted toward sustainable practices due to the environmental and health hazards associated with synthetic dyes. Plant-based natural dyes have re-emerged as viable alternatives, particularly in handloom textiles, which are deeply connected to traditional craftsmanship and ecological balance. Historically, plant dyes were the primary source of textile coloration before the introduction of synthetic dyes in the 19th century. In countries like India, handloom sectors continue to rely on plant-based dyes for producing eco-friendly fabrics that cater to niche markets emphasizing organic and sustainable products. The revival of plant dyes is driven by consumer awareness, government regulations, and the growing demand for green textiles (Devi et al., 2025; Pizzicato et al., 2023).

II. SOURCES OF PLANT-BASED NATURAL DYES

Plant-based dyes are obtained from various parts of plants, including leaves, roots, bark, flowers, seeds, and fruits, each contributing different color shades and properties. Leaves such as those from indigo plants produce blue dyes, while roots like madder yield red tones. Bark from trees such as acacia provides brown and tan shades, and flowers like marigold and hibiscus produce yellow and orange hues. Fruits and peels, such as pomegranate rind, are also widely used due to their rich tannin content, which enhances dye fixation. The diversity of plant sources enables a broad spectrum of colors, although the shades are generally softer and more subdued compared to synthetic dyes. Recent studies have also explored the use of agricultural waste materials such as onion skins and tea leaves as sustainable dye sources, promoting circular economy practices (Baaka et al., 2024; Saxena & Raja, 2014).

III. CHARACTERISTICS OF PLANT-BASED NATURAL DYES

Plant-based dyes are widely recognized for their eco-friendly and biodegradable nature, making them suitable for sustainable textile production. Unlike synthetic dyes, they do not release toxic effluents into water systems, thereby reducing environmental pollution. Another important characteristic is their non-toxic and hypoallergenic nature, which makes them safe for skin contact and suitable for garments used in daily wear. These dyes produce soft, earthy tones with unique variations, enhancing the aesthetic appeal of handloom textiles. Additionally, many plant dyes possess functional properties such as antimicrobial, antioxidant, and ultraviolet (UV) protection, which add value to the final textile product. However, plant dyes generally exhibit lower color fastness to washing and light, which is considered a major limitation. This issue is often addressed by using mordants such as alum, iron, and tannin to improve dye fixation and durability (Nadeem et al., 2024; Yusuf et al., 2017).

IV. TYPES OF PLANT-BASED NATURAL DYES

Plant-based natural dyes can be classified based on their chemical composition, source, and method of application. These classifications help in understanding their dyeing behavior, color yield, and suitability for different textile materials.

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A. Classification Based on Chemical Composition

1) Indigoid Dyes: Indigoid dyes are among the oldest and most important natural dyes, primarily obtained from plants such as Indigofera tinctoria. These dyes produce blue shades and are unique because they are applied through a reduction–oxidation (vat dyeing) process. Indigo does not require a mordant, as it forms an insoluble pigment within the fiber, resulting in relatively good color fastness compared to other natural dyes (Bechtold & Mussak, 2009; Yusuf et al., 2017).
2) Anthraquinone Dyes: Anthraquinone dyes are responsible for red shades and are commonly extracted from plant roots such as madder (Rubia tinctorum). These dyes provide bright and stable colors and exhibit better light fastness than many other natural dyes. They require mordants to bind effectively with textile fibers (Shahid & Mohammad, 2013).
3) Flavonoid Dyes: Flavonoids are a large group of plant pigments that produce yellow, cream, and light brown shades. They are commonly found in plants such as turmeric (Curcuma longa), onion skins, and marigold flowers. Flavonoid dyes often have antioxidant and antimicrobial properties but generally show moderate fastness unless treated with mordants (Saxena & Raja, 2014; Nadeem et al., 2024).
4) Tannin-Based Dyes: Tannins are polyphenolic compounds found in bark, leaves, and fruits such as pomegranate and myrobalan. These dyes produce brown and grey shades and are often used as natural mordants due to their strong affinity for fibers. Tannin-based dyes enhance dye fixation and improve overall color fastness (Prabhu & Bhute, 2012).
5) Carotenoid Dyes: Carotenoids produce yellow, orange, and red colors and are found in plants such as carrots, annatto seeds, and marigold flowers. These dyes are sensitive to light and oxidation, which limits their durability in textile applications (Ali et al., 2010).

V. CLASSIFICATION BASED ON PLANT PARTS USED

1) Leaf Dyes: Leaf-based dyes are primarily used to produce green and blue shades. Indigo is the most prominent example, widely used in handloom textiles for its deep blue color. Leaves are easily available and renewable, making them a sustainable dye source (Siva, 2007).
2) Root Dyes: Roots such as madder and turmeric provide strong and vibrant colors, especially reds and yellows. These dyes generally have better affinity for natural fibers and are widely used in traditional dyeing processes.
3) Bark and Wood Dyes: Tree bark and wood extracts produce earthy tones such as brown, tan, and grey. These dyes are rich in tannins and are often used for darker shades and improved fastness properties (Gulrajani, 2011).
4) Flower Dyes: Flowers such as marigold, hibiscus, and safflower yield bright and vibrant colors. They are commonly used in decorative and artistic textile applications, including handloom fabrics and printed textiles.
5) Fruit and Peel Dyes: Fruits and their peels, such as pomegranate rind and berry extracts, are rich in tannins and natural pigments. These dyes are increasingly used due to their availability and sustainability, especially as waste-derived dye sources (Baaka et al., 2024).

VI. CLASSIFICATION BASED ON APPLICATION METHOD

1) Mordant Dyes: Most plant-based dyes fall under this category and require mordants such as alum, iron, or tannin to fix the dye onto the fabric. Mordants also influence the final shade and improve fastness properties (Samanta & Agarwal, 2009).
2) Vat Dyes: Indigo is the primary example of a natural vat dye. It is insoluble in water and requires reduction to a soluble form before dyeing. Once applied, it oxidizes back to its insoluble form, fixing permanently onto the fiber.
3) Direct Dyes: Some plant dyes can be applied directly to fibers without the use of mordants, although their fastness properties are usually lower.

VII. EXTRACTION AND DYEING PROCESS

The extraction of plant-based dyes involves boiling or soaking plant materials in water or other solvents to release the coloring compounds. The extracted dye solution is then filtered and used for dyeing yarns or fabrics. Mordanting is a crucial step in the dyeing process, where textile fibers are treated with substances like alum or tannins to enhance dye absorption and improve color fastness. Dyeing techniques in handloom textiles include exhaust dyeing, where the fabric is immersed in the dye bath, and traditional methods such as vat dyeing for indigo. The process is often time-consuming and requires careful control of parameters such as temperature, pH, and dye concentration. Despite these challenges, advancements such as ultrasonic-assisted extraction and eco-friendly mordants are being explored to improve efficiency and sustainability (Sharma et al., 2020; Nadeem et al., 2024).

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VIII. USES OF PLANT-BASED DYES IN HANDLOOM TEXTILES

Plant-based dyes are extensively used in handloom textiles for producing a wide range of products, including sarees, dupattas, scarves, shawls, and traditional garments. These textiles are highly valued in both domestic and international markets due to their eco-friendly nature and unique aesthetic appeal. In addition to apparel, plant-dyed fabrics are also used in home textiles such as curtains, bedspreads, and cushion covers. The demand for plant-dyed handloom products is particularly high in the organic and sustainable fashion sectors, where consumers prefer environmentally responsible products. The use of plant dyes also supports rural artisans and promotes traditional knowledge systems, contributing to socio-economic development (Gulrajani, 2011; Cardon, 2007).

IX. APPLICATIONS IN HANDLOOM TEXTILES

Plant-based dyes are applied in various stages of handloom textile production, including yarn dyeing, fabric dyeing, and printing. In yarn dyeing, fibers are dyed before weaving to achieve uniform coloration and intricate patterns. Fabric dyeing is carried out after weaving to produce solid or gradient shades. Plant dyes are also widely used in traditional printing techniques such as block printing, tie-dye, and batik, which enhance the artistic value of handloom textiles. Furthermore, plant dyes are increasingly used in the development of functional textiles with added properties such as antimicrobial and UV protection. These applications highlight the versatility of plant-based dyes in both traditional and modern textile practices (Samanta & Agarwal, 2009; Prabhu & Bhute, 2012).

X. ADVANTAGES OF PLANT-BASED DYES

Plant-based dyes offer numerous advantages, including environmental sustainability, biodegradability, and safety for human health. They reduce dependency on synthetic chemicals and promote the use of renewable resources. The unique and naturally varying shades produced by plant dyes add exclusivity to handloom textiles, making them highly desirable in niche markets. Additionally, the use of plant dyes supports traditional artisans and contributes to the preservation of cultural heritage. Their compatibility with eco-friendly textile processing techniques further enhances their appeal in sustainable fashion (Ali et al., 2010; Siva, 2007).

XI. LIMITATIONS AND CHALLENGES

Despite their benefits, plant-based dyes face several challenges that limit their widespread industrial adoption. The primary limitation is their poor color fastness compared to synthetic dyes, which affects the durability of dyed textiles. The availability of raw materials is often seasonal, leading to inconsistency in production. Additionally, the dyeing process is labor-intensive and time-consuming, which increases production costs. There is also a lack of standardization in dye extraction and application methods, resulting in variations in color quality. Addressing these challenges requires continued research and technological advancements (Singh & Jain, 2012; Mahale et al., 2021).

XII. RECENT ADVANCES IN PLANT-BASED DYE RESEARCH

Recent research in plant-based dyes focuses on improving their performance and expanding their applications. Innovations such as the use of bio-mordants, enzyme-assisted extraction, and nanotechnology are being explored to enhance dye uptake and fastness properties. The utilization of agricultural waste as dye sources is gaining attention as a sustainable approach to reduce waste and promote circular economy practices. Additionally, plant dyes are being integrated with functional finishes to develop multifunctional textiles with antimicrobial and UV-protective properties. These advancements are expected to increase the commercial viability of plant-based dyes in the textile industry (El-Bassuony et al., 2025; Baaka et al., 2024).

XIII. CONCLUSION

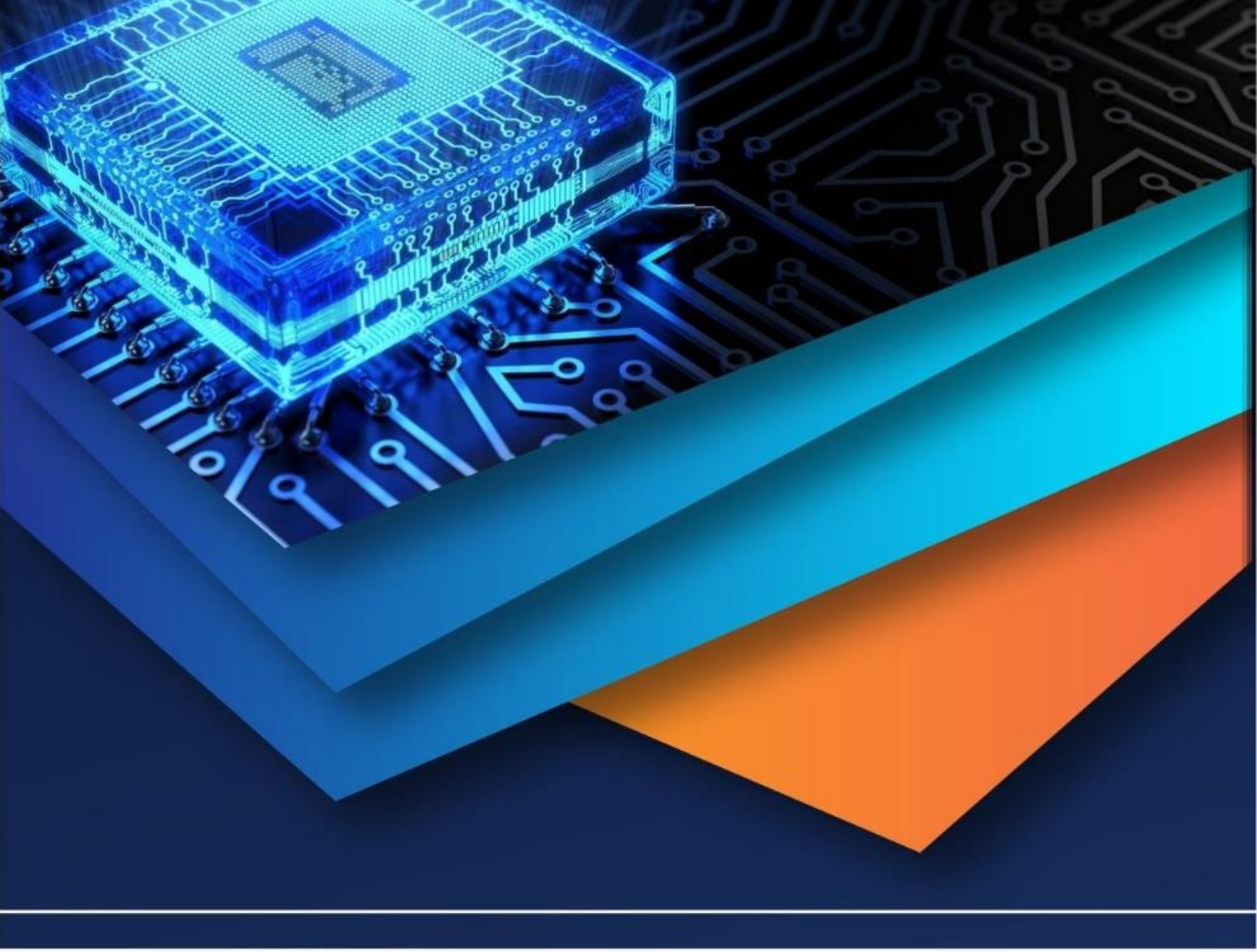
Plant-based natural dyes play a vital role in promoting sustainability and preserving the cultural heritage of handloom textiles. Their eco-friendly nature, combined with aesthetic and functional benefits, makes them a promising alternative to synthetic dyes. Although challenges such as low color fastness and high production costs persist, ongoing research and technological innovations are addressing these limitations. The growing demand for sustainable and organic textiles is expected to drive the increased adoption of plant-based dyes in the future, particularly in handloom sectors that emphasize traditional and environmentally responsible practices.

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