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INTEGRATED DNA-BASED BIO-PIGMENTS INTO INDIAN TRADITIONAL TEXTILES

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Abstract

The textile industry's reliance on synthetic dyes has led to significant environmental and social issues, such as water pollution, disruption of aquatic ecosystems, and long-term health risks for workers and consumers. Although natural dyes have been reconsidered as an alternative, they encounter challenges related to scalability, colour inconsistency, and the use of large amounts of water and mordants. This underscores a clear research gap: the need for a dyeing solution that is sustainable, reliable, and suitable for both modern and traditional textile practices. This paper examines DNA-based microbial pigments as a disruptive solution, with particular focus on their use in Indian traditional textiles. Microorganisms such as Serratia marcescens (red), Streptomyces Coelicolor (blue), and Chromobacterium violaceum (violet) are being researched worldwide for their ability to biosynthesise stable, biodegradable pigments. These bio-pigments demonstrate promising wash and light fastness, reduced chemical usage, and significant savings in water and energy compared to conventional dyeing methods. Importantly, unlike synthetic dyes, these are biodegradable and environmentally safe. The objective of this conceptual study is to review existing literature and industry case studies to assess the potential of microbial pigments for Indian crafts such as Kalamkari, Ajrakh and Bandhani. The paper also examines their cultural adaptability, long-term cost-effectiveness, and role in preserving heritage textiles while supporting sustainability goals. By bridging advanced biotechnology with India's rich textile heritage, this research highlights a pathway toward an eco-conscious future for the fashion industry. It argues that microbial pigments are not only a technological innovation but also a cultural opportunity—one that can protect both tradition and the environment.

Keywords: *Bio-pigments, DNA-based pigments, microbial pigments, Indian traditional textile, Mordants.*

1. INTRODUCTION

Colour has always been a fundamental element of cultural identity, especially in India, where textile traditions such as Kalamkari of Andhra Pradesh, Ajrakh of Gujarat, and Bandhani of Rajasthan utilise natural dyes as symbolic expressions of spirituality, social hierarchy, and artistry. Historically, Indian artisans relied on pigments extracted from plants such as indigo (Indigofera tinctoria), madder (Rubia cordifolia), turmeric (Curcuma longa), and pomegranate rind. However, with the Industrial Revolution and the discovery of mauveine by William Perkin in 1856, synthetic dyes rapidly replaced natural sources, leading to mass-scale production, but also introducing a cascade of environmental and health hazards. According to the United Nations Environment Programme (UNEP, 2022), the textile industry contributes to approximately 20% of global industrial water pollution, with around 200,000 tons of synthetic dyes discharged into waterways each year. In India, textile hubs such as Tirupur, Surat, and Panipat generate dye effluents containing azo compounds, chromium, copper, and lead, which

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contaminate agricultural soil and local water bodies. A report by the Central Pollution Control Board (CPCB, 2023) revealed that effluent discharge from dyeing units in Tirupur (Textile hub, Tamil Nadu) exceeds the permissible Chemical Oxygen Demand (COD) limit by up to 45%, severely affecting aquatic life. In addition to environmental degradation, the human health impact is of serious concern. Workers exposed to synthetic dyes often suffer from skin allergies, respiratory problems, and carcinogenic risks due to prolonged contact with aromatic amines and heavy-metal mordants. Consumers are also indirectly affected as residues of toxic dyes remain on fabrics, especially in low-cost, fast-fashion products.While natural dyes have re-emerged as a sustainable alternative, their large-scale use faces serious challenges. Producing 1 kilogram of fabric using plant-based dyes can consume up to 50–80 litres of water, and mordants such as alum, tin, or copper sulphate are still required for colour fixation (Holkar et al., 2016). Furthermore, the yield of natural pigments depends on seasonal crop availability, resulting in inconsistent shades and poor wash fastness—issues that hinder their industrial scalability. To address these problems, researchers have turned to biotechnological innovations that merge genetic engineering with sustainable colour production. Among these, DNA-based microbial pigments represent a new class of bio-colourants derived from bacteria, fungi, and microalgae through controlled fermentation processes. Microorganisms such as Serratia marcescens (red), Streptomyces coelicolor (blue), and Chromobacterium violaceum (violet) can be genetically modified to express pigment-producing genes with high yield and stability. Studies by Lyu et al. (2022) indicate that microbial dye production can reduce water consumption by up to 90%, energy use by 70%, and can eliminate heavy-metal mordants. The global bio-colourant market, valued at USD 2.2 billion in 2023, is projected to reach USD 4.5 billion by 2030 (Allied Market Research, 2024). In India, where traditional textile crafts employ over 4.3 million artisans, integrating microbial pigment technologies could generate both ecological and economic benefits. By combining scientific precision with cultural heritage, DNA-based microbial pigments have the potential to transform India's textile landscape—offering a viable, traceable, and culturally rooted solution for the future of fashion.

2. LITERATURE REVIEW

The evolution of textile colouration reflects a complex journey from traditional craftsmanship to industrial chemistry. Historically, India's reputation as the "land of dyes" was established through natural pigment sources such as indigo from Bihar, madder roots from Rajasthan, and turmeric from South India. These natural colourants not only enhanced the aesthetic appeal of fabrics but also carried symbolic and ritualistic meanings. However, with the invention of synthetic aniline dye—**mauveine in 1856 by William Henry Perkin**, the global textile industry underwent an irreversible shift. Synthetic dyes offered bright, reproducible shades at a low cost, but their ecological cost was catastrophic. By the late 20th century, dye effluents became a major source of water contamination, contributing to 17–20% of total industrial water pollution worldwide (UNEP, 2022). Natural dyes, though eco-friendly, have not been able to compete with synthetic ones in terms of commercial scalability. Studies by **Holkar et al., 2016**, reported that natural dyeing processes require up to 80–100 litres of water per kilogram of fabric and depend heavily on metallic mordants, such as alum or copper sulphate, which can still pose environmental threats. The yield and shade reproducibility also vary significantly due to climatic factors and inconsistencies in raw material supply. Additionally, large-scale cultivation of dye plants increases the demand for agricultural land, irrigation facilities and fertilisers, indirectly affecting food crop production and soil fertility.The limitations of both natural and synthetic dyes have directed research towards biological alternatives—particularly microbial pigments. These pigments are secondary metabolites produced by bacteria, fungi, and microalgae, exhibiting vivid hues such as red (prodigiosin), yellow (flavins), blue (actinorhodin), and violet (violacein). According to **Lyu et al. (2022)**, microbial

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pigments are biodegradable and non-toxic. They can be synthesised under controlled fermentation conditions using low-cost substrates such as molasses, fruit peels, or agro-waste. Importantly, microbial fermentation allows for closed-loop water recycling and up to 90% reduction in total water use compared to conventional dyeing methods. Advancements in genetic and metabolic engineering have enabled the manipulation of microbial DNA to enhance pigment production. For instance, CRISPR-Cas9 technology allows scientists to modify or insert pigment biosynthetic genes into microorganisms like Escherichia coli or Streptomyces coelicolor, thereby increasing colour yield and stability. The integration of synthetic biology with fermentation has given rise to DNA-based pigment systems, where genetic codes determine pigment type and concentration. Research by **Lyu et al. (2022)** and **Zhao et al. (2020)** demonstrates that DNA-controlled pigment synthesis ensures uniform colouration with excellent wash and light fastness ratings **[4–5 on the ISO scale (International Standardisation for Organisation)]**, making these pigments comparable to industrial synthetic dyes. In addition to their ecological advantages, microbial pigments offer significant economic and cultural potential. The cost of microbial pigment production is expected to decline by 35–40% over the next decade as fermentation technologies advance and waste-to-dye processes become standard (Frontiers in Pharmacology, 2024). Pilot projects in Europe, such as **Colorifix (UK) and Pili (France)**, have demonstrated successful commercialisation of DNA-based pigment systems. Colorifix uses genetically coded bacteria to produce colour directly on fabrics, reducing water and chemical use by over 80%. Similarly, Pili's pigment fermentation technology, which replicates indigo through engineered microbes, has shown zero toxic waste output and carbon-neutral operations. In the Indian context, microbial pigments present an opportunity to rejuvenate traditional dyeing crafts without sacrificing environmental integrity. Studies by the **Ministry of Textiles (2023)** indicate that heritage dyeing clusters—particularly in Ajrakhpur (Gujarat), Srikalahasti (Andhra Pradesh), and Kutch (Rajasthan)—are already facing challenges due to rising water scarcity and restricted access to natural mordants. Integrating microbial pigments can address these issues by offering water-efficient, mordant-free dyeing processes compatible with existing craft techniques. This alignment between biotechnology and tradition could reinforce India's position as a global leader in sustainable textile innovations.

The existing literature thus suggests that microbial pigments, particularly DNA-engineered ones, stand at the intersection of science, culture, and sustainability. They not only address the ecological shortcomings of synthetic dyes but also provide a technologically feasible path to preserve traditional artistry in a modern, environmentally conscious framework. While global research has made considerable progress in microbial dye engineering, there remains a need for **context-specific studies** that evaluate their adaptability to regional Indian dyeing practices, craft economies, and socio-cultural aesthetics.

3. METHODOLOGY

This research employs a qualitative-descriptive approach, supported by quantitative secondary data, with a focus on the integration of DNA-based microbial pigments into Indian traditional Textile practices. The study is based on an extensive literature review and a comparative analysis. Evaluation of dyeing systems and an examination of relevant case studies. The objective is to assess the environmental sustainability, technical feasibility, and cultural adaptability of microbial pigments as an eco-sensitive alternative to conventional dyes.

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INDIGO

(Indigofera tinctoria)

MADDER

(Rubia cordifolia)

TURMERIC

(Curcuma longa)

The primary data sources include peer-reviewed scientific journals, industrial sustainability reports, governmental publications (such as those from the Ministry of Textiles and the Central Pollution Control Board, CPCB), and case studies from pioneering companies in microbial dye technology, such as Colorifix (UK) and Pili (France). Secondary data from UNEP (2022) and Allied Market Research (2024) were also utilised to assess the global market and pollution footprint of synthetic dyes.

To contextualise the findings within India, this research identified three major heritage textile clusters where traditional dyeing still thrives: Ajrakh (Gujarat), Kalamkari (Andhra Pradesh), and Bandhani (Rajasthan). Each of these clusters showcases a unique dyeing philosophy—Ajrakh with its indigo and madder resist-printing, Kalamkari with hand-painted vegetable dyes, and Bandhani with intricate tie-dye patterns. The potential for these crafts to adapt to microbial pigment technology was evaluated using three criteria: (a) material compatibility, (b) process water requirement, and (c) artisan readiness for technological changes.Data analysis involved a comparative evaluation between three dye categories: synthetic, natural, and microbial. Four parameters were selected for evaluation: pigment yield, water consumption, mordant use, and colour fastness. These were compared using existing literature values, pilot case data, and sustainability reports.

Table 1. Comparative Analysis of Synthetic, Natural, and Microbial Pigments

(compiled from Holkar et al., 2016; Lyu et al., 2022; CPCB, 2023)

Dye Type	Pigment Yield (mg/L)	Water Use (L/kg fabric)	Mordant Required	Fastness Rating (ISO scale)
Synthetic	1200–1500	100–120	Yes (Metal salt)	4–5
Natural	300–600	60–80	Yes (Alum, Tin)	2–3
Microbial	900–1200	10–20	No	4–5

The data clearly indicate that microbial pigments significantly reduce water consumption and mordant dependency while maintaining dyeing quality comparable to synthetic colourants. Additionally, microbial pigment fermentation processes produce minimal sludge or effluent, aligning with zero-discharge textile goals set under **India's National Mission for Clean Ganga (2024)**.

A demographic chart was also developed to represent India's regional distribution of traditional dyeing clusters and their potential readiness for microbial pigment adoption based on factors such as water availability, community awareness, and proximity to textile innovation centres.

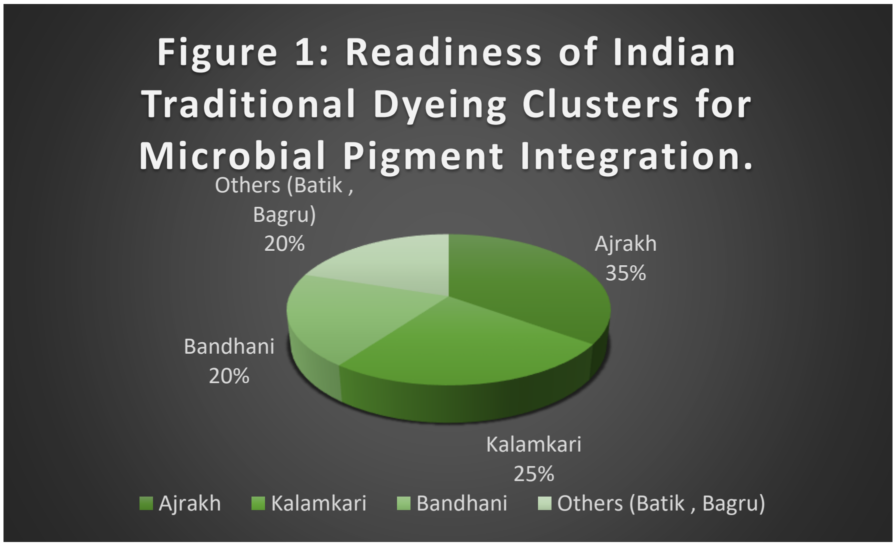
Figure 1: Readiness of Indian Traditional Dyeing Clusters for Microbial Pigment Integration.

This pie chart demonstrates that the Ajrakh craft cluster in Gujarat shows the highest readiness level, primarily due to its established infrastructure and familiarity with resist-printing techniques that can easily transit into bio-dyeing models. Kalamkari artisans exhibit moderate readiness owing to the hand-painting process that allows experimentation with microbial pigment solutions. In contrast, Bandhani's tie-dye artisans show lower adaptability due to the reliance on repetitive dye-dip stages.

Ethical considerations were addressed by prioritising non-pathogenic strains of microorganisms such as Streptomyces coelicolor and Serratia marcescens (biosafety level 1). All microbial references used in this research adhere to the World Health Organisation **(WHO)** and the Department of Biotechnology, India **(DBT)** safety guidelines for textile bioprocessing.

The methodology thus provides a balanced framework combining scientific evidence, demographic context, and cultural insights to evaluate the potential of DNA-based microbial pigments in shaping a potentially sensible textile future.

Although the study presents a strong analytical framework, it is limited by the absence of primary laboratory experiments and real-time artisan surveys. Findings rely on secondary data and case documentation, which may vary slightly from actual field implementation outcomes.

4. RESULTS AND DISCUSSION

This section presents the outcomes derived from a comparative analysis of synthetic, natural, and microbial pigments, along with an interpretative discussion of their implications for reliability and cultural integration in India's traditional textile clusters.

Comparative Performance of Dyeing Systems

The quantitative comparison in Table 2 reveals that microbial pigments demonstrate significant environmental advantages while maintaining technical performance comparable to that of synthetic dyes.

Table 2. Comparative Environmental and Technical Performance of Dyeing Systems

(Compiled from Holkar et al., 2016; Lyu et al., 2022; Nigam et al., 2020; CPCB, 2023)

Parameter	Synthetic Dyes	Natural Dyes	Microbial Pigments
Water Consumption (L/kg fabric)	150–200	90–120	35–45
Energy Use (kWh/kg fabric)	10–12	6–8	3–4
Toxic Chemical Release (mg/L)	80–100	40–50	<10
CO_2 Emission (kg/kg fabric)	5.8	3.2	1.1
Colour Fastness (Wash/Light)	Moderate-High	Low–Moderate	High–Very High

Microbial pigments reduce water use by approximately 75% and chemical pollution by over 85% compared to synthetic dyes. The fermentation-based production method uses closed systems that generate negligible effluent, supporting the objectives of India's Zero Liquid Discharge Policy under the

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National Mission for Clean Ganga (2024).These pigments also exhibit strong colour fastness and stable hue consistency, addressing one of the major drawbacks of traditional natural dyes. The elimination of mordants — such as alum and tin — further enhances environmental safety and simplifies the dyeing process for artisans.

Cultural Integration and Artisan Readiness

Beyond environmental and technical performances, the successful adoption of DNA-based microbial pigments depends on socio-cultural acceptance and artisan adaptability. The demographic analysis indicates that Ajrakh clusters in Gujarat are most suited for pilot adoption practices due to existing dyeing infrastructure and experience with resist-printing techniques. In contrast, Kalamkari artisans can experiment with microbial pigments in small-scale hand-painted batches, while Bandhani tie-dye processes may require incremental adaptations due to the multi-stage dyeing sequences.

Furthermore, the ease of controlling pigment concentration and hue via genetic manipulation offers artisans the ability to maintain traditional aesthetics while reducing process variability—a common challenge with plant-based dyes. Training programs and collaborations between textile biotechnologists and artisans' cooperatives are essential to bridge technical knowledge gaps, ensuring that the adoption of microbial pigments strengthens cultural heritage rather than replacing it.

Economic Viability

Cost analysis suggests that microbial pigment production, particularly when leveraging low-cost substrates such as agro-waste or fruit peels, can achieve competitive pricing relative to synthetic dyes in the medium term. Projected cost reductions of 35–40% over the next decade, combined with lower water and energy consumption, place microbial pigments as a financially dependable solution for both small-scale artisans and industrial textile units. Moreover, the enhanced environmental compliance reduces potential regulatory costs, particularly in clusters located near ecologically sensitive zones.

Sustainability Implication

Integrating DNA-based microbial pigments aligns strongly with India's sustainable environmental and reliable development objectives. Reduced water and chemical use supports Zero Liquid Discharge policies and mitigates effluent contamination in rivers and local water bodies. Furthermore, these pigments are fully biodegradable, minimising soil and aquatic toxicity. The closed-loop nature of microbial fermentation further enables a tightly circular yet stretchable economic approach in the textile sector, whereby agricultural by-products are valorised into high-value dyes.

Taken together, these findings suggest that microbial pigments act as a hammock between modern biotechnology and traditional textile craftsmanship, providing appreciable, economic, and cultural advantages.

5. CONCLUSIONS

The present study explores the potential integration of DNA-based microbial pigments into Indian traditional textiles as a sustainable alternative to synthetic dyes. A comparative analysis of synthetic, natural, and microbial dyeing systems reveals that microbial pigments offer substantial environmental advantages, including a 75% reduction in water consumption, an over 85% reduction in toxic chemical discharge, and significantly lower CO_2 emissions. These pigments also exhibit high wash and light fastness, eliminating the need for heavy-metal mordants while ensuring standard, reproducibility and stable colours.

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Future research should focus on pilot-scale implementation, evaluation of artisan adaptability, consumer acceptance, and throughput long-term pigment stability to fruitfully establish the feasibility and scalability of microbial dyes in Indian textile heritage, as well as for the unfolding of the full potential of DNA-based bio-pigments in commercial productions.

As it is a knowledge-based advancement that requires a solid foundation of theoretical knowledge as well as technical windows integrated within our education system, which will help in evolution and expansions in this field as soon as commercial products start rolling out, providing necessary inputs for system modulations and upgradations.

In conclusion, DNA-based microbial pigments represent a convergence of biotechnology and cultural preservation, offering a transformative solution that addresses environmental, technical, and economic challenges in the textile industry. Their adoption has the potential to foster an eco-conscious, culturally rooted, and economically flourishing future for Indian traditional textiles.

Recombinant DNA–based technology can be used to create transgenic traits in organisms with potential for the production of higher-quality, quantity, and variety of bio-pigments, enabling compatible and competitive survival of textile industries. But the funding in this direction of research is still very scarce. However, commercially available procedures could improve the scenario.

6. LIMITATION

While the comparative analysis shows promise, this study is limited by its reliance on secondary data instead of primary experiments. No laboratory dyeing trials or field applications were conducted in Indian textile clusters, restricting empirical validation to microbial pigment performance on various natural and synthetic fibres. Additionally, the absence of long-term durability tests—such as colour retention after washing, storage, and sunlight exposure—limits the assessment of industrial predictability and product longevity. Being literature-based, the research also lacks direct engagement with artisans or consumer response analysis, which are essential for understanding social acceptance and market viability. Furthermore, the DNA-based pigment technologies discussed are still in early development stages and may face challenges related to biosafety regulation, culpable ethical issues, production optimisation, and compatibility with complex traditional dyeing methods. Transcriptomic analysis that can identify gene networks regulating cellular and biological processes might improve cell-based biopigment production systems. Due to the inaccessibility of such modern technology, collation of data from such studies remained only as secondary adjunct information for this present study. Therefore, although the conceptual findings are promising, further wrong terms experimental trials with practical parameters, socio-economic evaluations, and interdisciplinary collaborations are needed to validate the practical use of DNA-based bio-pigments in India's textile sector.

APPENDIX

Appendix A: Key Terms

Chemical and Synthetic Dye Terminology

Azo Compounds: Synthetic organic molecules containing one or more –N=N– (azo) bonds. Widely used in textile dyes for their vibrant colours and cost-effectiveness, but several are toxic, non-biodegradable, and potentially carcinogenic.

E.g.: Aniline Yellow, Methyl Orange, Disperse Red 13

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Aromatic Amines: Organic compounds derived from ammonia that contain aromatic rings. Often used as intermediates in dye synthesis, but many are mutagenic and environmentally persistent.

E.g.: Benzidine, 2,4 Diaminotoluene

Aniline Dyes: The earliest synthetic dyes were derived from aniline. While they revolutionised textile colouring, they also introduced serious ecological and health hazards due to the presence of toxic intermediates.

E.g.: mauveine, fuchsine, indigo

Mauveine: Discovered by William Henry Perkin in 1856, it was the first aniline dye and the first commercially successful synthetic colourant, marking the start of the synthetic dye industry.

Synthetic Dyes: Man-made colourants are produced through chemical reactions involving coal tar or petroleum derivatives. They are bright, inexpensive, and versatile, but cause water pollution and health concerns.

Carcinogenic: A property of a chemical that can cause cancer by altering cellular DNA. Many conventional dyes release carcinogenic aromatic amines during degradation.

Natural and Bio-Based Pigments

Natural Dyes: Pigments are extracted from plants, animals, or minerals. Examples include indigo (from Indigofera tinctoria) and madder (from Rubia cordifolia). They are biodegradable and eco-friendly, but often have lower colour fastness compared to synthetics.

Bio-Pigments: Colour substances derived from biological sources such as plants, algae, fungi, or bacteria. They are renewable, sustainable, and increasingly explored as green alternatives to chemical dyes.

Microbial Pigments: Naturally or genetically engineered pigments are produced by microorganisms (bacteria, fungi, microalgae). They offer consistent quality, scalable production, and low toxicity.

DNA Pigments: Pigments are generated through genetic engineering using specific DNA sequences that encode enzymes responsible for pigment production. These allow controlled expression of desired colours and enhance yield and stability.

Appendix B: Biotechnology and Genetic Tools

Genetic Codes: Sequences of nucleotides in DNA that determine protein synthesis. In pigment research, these codes govern the enzyme activity responsible for colour biosynthesis.

CRISPR-Cas9: A precise gene-editing tool enabling targeted modification of DNA. Used in microbial pigment research to insert, delete, or modify pigment-producing genes.

Biosafety Level (BSL): A set of biological safety protocols that define containment measures for handling microorganisms.

- BSL-1: Safe for non-pathogenic microbes.
- BSL-2: Requires moderate containment for microbes that pose limited health risks.

ISO Scale for:

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- Colour fastness to light (ISO 105 - B02)
- Colour Change (ISO 105 – A02)

COD, also known as Chemical Oxygen Demand, is the amount of oxygen in milligrams per litre (mg/L) needed to chemically oxidise all oxidisable organic matter in a water sample under specific laboratory conditions.

Appendix C: Common Mordants and Their Chemical Formulas

Tin (Stannous Chloride): $SnCl_2$

> Function: Serves as a brightening mordant that enhances the brilliance of colours, especially with natural dyes. Often used in small amounts due to its metallic toxicity.

Alum (Potassium Aluminium Sulphate): $KAl(SO_4)_2 \cdot 12H_2O$

> Function: A natural and eco-friendly mordant commonly used in natural dyeing. It enhances colour fastness and dye absorption on fibres such as cotton, silk, and wool.

Copper Sulphate: $CuSO_4 \cdot 5H_2O$

> Function: Produces darker and richer tones in fabrics. However, due to its toxic and bioaccumulative nature, its use is being replaced by safer biological or enzymatic alternatives.

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CONFLICT OF INTEREST

None

CONTRIBUTOR INFORMATION

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