

Bio-Mordants Revolutionize With Nanotechnology For Natural Dyeing Of Textiles – An Analytical Review

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This extensive review explores recent developments in utilising plant-based bio-mordants as eco-friendly substitutes for traditional metal mordants in natural fabric dyeing. Concentrating on research from the last five years, the review evaluates the efficacy, extraction techniques, and multifunctional characteristics of various bio-mordants, with a particular focus on banana pseudostem sap. Principal outcomes suggest that bio-mordants such as *Terminalia chebula*, pomegranate rind, and gallnut can improve colour fastness and intensity to levels matching or surpassing those of metal mordants. Refinement of extraction and application methods, including microwave-assisted techniques, has enhanced dyeing results. Fabrics treated with bio-mordants demonstrate additional functional qualities like antimicrobial properties and UV protection. The review also highlights research deficiencies, including limited large-scale industrial applications, absence of standardised protocols, and insufficient data on long-term durability. Overall, nanosynthesis of bio-mordants for natural textile dyeing is an emerging field, offering promising sustainable alternatives to traditional mordants, but requires further research to optimize processes and enable widespread industrial adoption. The utilisation of agricultural by-products, such as banana pseudostem, as a source of bio-mordants, illustrates opportunities for developing circular economy approaches in textile manufacturing.

Keywords: Natural Dyeing, Bio-mordants, Banana Pseudostem, Nanotechnology, Colourfastness, Multifunctional Properties

1. Introduction

The textile industry faces increasing pressure to adopt more sustainable and environmentally friendly practices, particularly in dyeing processes that traditionally rely on synthetic dyes and metal ion dependant dyes. This comprehensive review examines recent advances in the application of bio-mordants derived from plant sources as alternatives to conventional metal mordants in natural textile dyeing. Focusing on studies published in the last five years, this article analyzes the effectiveness, extraction methods, and multifunctional properties of various bio-mordants, with particular emphasis on banana pseudostem sap. Natural dyeing processes often incorporate metal ions as mordants to enhance the interaction between dyes and fibers, resulting in improved color fastness and intensity. Frequently used metal mordants

include iron (ferrous sulfate), copper (copper sulfate), tin (stannous chloride), and chrome (potassium dichromate). These mordants form chemical bonds between dye molecules and fibers, enhancing color retention and fade resistance. However, certain metal mordants pose environmental and health risks, necessitating the use of biomordants. The review explores three key areas: 1) Comparative analysis of plant-based bio-mordants versus metal mordants, highlighting their relative performance in enhancing color fastness and intensity.

2) Optimization of extraction and application techniques for banana pseudostem sap as a bio-mordant, examining its potential to maximize dyeing performance, and 3) Evaluation of the multifunctional properties of bio-mordants, including their antimicrobial, UV-protective, and antioxidant capabilities. The review also identified research gaps, including limited industrial-scale application, incomplete understanding of mordanting mechanisms, narrow focus on natural fibers, and insufficient data on long-term stability of bio-mordanted textiles. Additionally, this paper explored the use of agricultural waste, specifically banana pseudostem sap. An insight on how as an eco-friendly bio-mordant does the banana pseudo stem contributes to improve color fastness, provide antibacterial properties, and mitigate environmental and health issues in the textile industry. This review paper critically synthesizes use of bio-mordant for naturally dyeing of different fabrics. The study aims to evaluate its effectiveness in improving color fastness, providing antibacterial properties, and addressing environmental and health issues in textile production. The use of this natural mordant could offer a sustainable alternative to conventional chemical mordants, potentially reducing the ecological impact of textile dyeing processes while enhancing fabric performance.

While natural dyeing techniques offer sustainable alternatives to synthetic dyes, nanotechnology presents opportunities to enhance the efficiency and performance of the dyeing processes by using nanoparticles of dyes and bio-mordants in the nanosynthesis. Nanosynthesis of bio-mordants is revolutionizing natural textile dyeing, offering a sustainable paradigm shift. While promising, this emerging field demands intensive research to refine processes and catalyze widespread industrial adoption, paving the way for eco-friendly textile production. Researchers can potentially improve color fastness, increase dye uptake, and introduce additional functional properties to textiles, bridging the gap between traditional practices and cutting-edge technological advancements.

2. Methodology

This approach ensures a comprehensive and systematic review of bio-mordants in sustainable textile dyeing. A thorough literature search utilising academic databases such as Google Scholar and Scopus was performed. Relevant keywords such as 'biomordants', 'mordants', 'natural dyeing', 'innovation in natural dyeing process', etc. were employed to identify recent peer-reviewed articles. The findings were evaluated for relevance and quality before extracting crucial data on bio-mordant categories, materials, techniques, and efficacy indicators. This data was subsequently organised into thematic categories and subjected to qualitative synthesis.

The methodologies were critically evaluated, consistencies and contradictions were identified, and practical implications were assessed. The findings were synthesised by addressing research objectives, integrating insights across themes, and identifying research gaps. Quality assurance was ensured through selection of research articles and thesis from indexed databases. The research articles were checked for proper citations, and multiple revisions were conducted. This systematic approach resulted in a critical yet a very comprehensive review of bio-mordants used in natural dyeing.

3. Literature Review

3.1 Introduction to Sustainable Textile Dyeing

Recent advances in sustainable textile dyeing have focused on developing environmentally benign alternatives to traditional metal mordants, with particular emphasis on bio-mordants derived from plant sources and agricultural waste products. The compatibility of bio-mordants and dyes on fabrics is a critical aspect of sustainable textile dyeing. Bio-mordants, obtained from plant sources and agricultural waste, offer an environmentally friendly alternative to traditional metal mordants. These natural mordants can enhance dye uptake, colour fastness, and overall dyeing performance on various fabric types. The compatibility of bio-mordants, dyes, and fabrics is a complex interplay of multiple factors. Ongoing research in this field aims to optimise these relationships, leading to more sustainable and efficient textile dyeing processes. It is observed through this review that the current body of research literature in the field of nanosynthesis for bio-mordant development is insufficient, which is a promising approach towards nano-synthesis of bio-mordants.

3.2 Bio-Mordants and its Impact

In a study conducted by Singh and Sheikh (2020), *Terminalia chebula*, a bio-mordant, was employed in the natural dyeing process of wool with *Kigelia Africana* dye. The researchers evaluated the colour and functional properties utilising standard methodologies. The resultant dyed wool fabric exhibited favourable colour attributes and fastness properties. Furthermore, the treated wool demonstrated remarkable antioxidant efficacy of up to 99.41%, antibacterial properties reaching 97.8%, and exceptional ultraviolet protection factor (UPF).

Rani et al. (2020) investigated the potential of utilising *Carica papaya* L. leaf dry powder extract as an eco-friendly natural dye for protein fabrics. The research compared the effects of various metal salts (ferrous sulfate, alum, and copper chloride) and natural tannin extracts (harda powder, pomegranate peel, orange peel, and amla powder) as mordants on the colour and fastness properties of dyed protein fabric samples. Dyeing experiments were conducted with and without mordants, employing pre-mordanting, meta-mordanting, and post-mordanting techniques. The study found that bio-mordants used in wool dyeing produced colour intensity and fastness properties comparable to metallic mordants. The bio-mordants yielded distinct colours, as expected from a mordant, offering a promising alternative to metal salts in wool dyeing for environmentally friendly textile colouration. The research quantified UV spectra, Fourier Transform Infrared (FTIR), antimicrobial, and Ultraviolet (UPF) values. Findings showed that both the dye extract and dyed samples demonstrated excellent antimicrobial properties. All dyed fabrics exhibited a bacterial colony counting reduction (%) exceeding 90% for both *S. aureus* and *E. coli* bacteria. Dyed textiles, particularly wool, showed

significant enhancement in UV protection. The UPF value of undyed wool increased from 79 to 704 after dyeing. Other fabrics showed modest UPF improvement due to their lower thickness and cover factor. The research concluded that *Carica papaya* L. leaf dry powder extract could serve as a viable alternative for dyeing medical textiles.

Jahangiri et al. (2018) examined the natural dyeing properties of woollen yarn treated with *Muria tinctorum* L. root extract. The study explored the effects of various tannin-rich plant extracts (*Rhus coriaria*, *Eucalyptus*, *Terminalia chebula*, *Quercus castaneifolia*, Pomegranate) and alum (a chemical mordant) on the colour characteristics of dyed samples using two mordanting methods (pre- and metamordanting). The researchers assessed the CIEDE2000 values, colour strength (K/S), washing fastness, and tensile properties of the mordanted and dyed specimens. Visually, a range of hues from orange to brownish-red were obtained. In general, samples pre-biomordanted with *Rhus coriaria* (10 % dry weight), *Eucalyptus* (10 % dry weight), *Terminalia chebula* (5 % dry weight), *Quercus castaneifolia* (5 % dry weight), and Pomegranate (5 % dry weight) demonstrated nearly equivalent colour difference (ΔE_{00}) and wash fastness values compared to samples treated with 3% dry weight alum. The implications of this study suggest that natural tannin-rich plant extracts could potentially serve as effective alternatives to chemical mordants like alum in wool dyeing processes. The comparable performance of these natural mordants in terms of color difference and wash fastness indicates that they suggest viable options for reducing the environmental impact of textile dyeing without compromising on quality. However, further research is needed to fully understand the long-term durability and real-world performance of naturally mordanted and dyed wool products across a wider range of applications and conditions.

Adeel et al. (2020) explored the potential of cinnamon bark as a yellow natural colourant for silk dyeing. The yellow pigment was isolated using different solvents and subjected to microwave drying for up to 6 minutes. Experiments showed that dyeing irradiated fabric at 35 °C for 45 minutes with a 3 pH irradiated extract containing 1 gramme of salt as a levelling agent yielded excellent results. The use of Al&Fe salt as sustainable chemical mordants, along with extracts of acacia, henna, rose, pomegranate, and turmeric as sustainable biomordants, not only produced new colours but also enhanced fastness ratings. Notably, the microwave treatment increased the amount of dye extracted from cinnamon bark and made the process more environmentally friendly and sustainable by using extracts from bio-mordants.

Habib et al. (2021) conducted a study to isolate the colorant from Arjun bark using an acidified methanolic medium and ultrasonic treatment. This environmentally friendly method significantly improved the color intensity of natural colorants extracted from Arjun bark on cotton fabric, even under mild conditions. The researchers also demonstrated the successful use of various bio-mordants, including 10% Zeera (*Cuminum cyminum*) extract, 3% Ilaichi (*Elettaria cardamomum*) extract, and 10% Harmal (*Peganum harmala*) and Neem (*Azadirachta indica*) extract. These bio-mordants not only enhanced the environmental friendliness, feasibility, and sustainability of the coloring process but also increased color intensity with a range of tonal effects from red to reddish-brown hues.

Research by Pinheiro et al. (2019) examined the effectiveness of *Acacia mearnsii* sawdust as a biomordant for colour retention. Experiments combining dyeing and colour fixation were performed on banana fibre using natural dyes extracted from *Hibiscus sabdariffa*, *Allium cepa*,

and *Curcuma longa*. The most favourable results were obtained by staining the fibres and applying a cold biomordant, then allowing a 24-hour rest bath followed by a 12-hour dyeing cycle. The findings indicated that *Acacia* could serve as an effective biomordant. The dyes examined proved to be effective biomordants, producing vivid hues whilst preserving the softness of the fibres. This study introduced novel approaches to natural dyeing by utilising sustainable methods and biomordants on various textile fibres. This innovative research transforms the natural dyeing of banana fiber, enhancing sustainability in textile production whilst conserving natural fibres.

To further explore the advantages of bio-mordants it is important to examine their specific mechanisms of action and their impact on various aspects of natural dyeing through the use of sustainable approach of nanotechnology. Bio-mordants used in green synthesis can enhance colour fastness by forming stable complexes between the dye and fabric. They improve dye uptake, penetration, and fixation, resulting in better colour retention after washing and exposure to light. Additionally, bio-mordants often contain tannins and other natural compounds that contribute to improved fastness properties while reducing environmental impact compared to traditional metal-based mordants.

3.3 Impact of Bio-Mordants on Colour Characteristics

A novel approach for dyeing wool samples in an eco-friendly and metal salt-free manner has been introduced by Shabbir et al. (2019). Metal-free salts are ionic compounds that do not contain any metal atoms. The lack of metal atoms gives these salts unique properties that can be advantageous in certain contexts, such as avoiding metal contamination or catalysis. However, they are generally less common than traditional metal-containing salts in most applications. This technique employs natural mordants extracted from pomegranate peel (*Punica granatum* L), gallnut (*Quercus infectoria* L), and catechu (*Acacia catechu*). The research revealed that the colour characteristics of the dyed wool samples were considerably affected by the chemical components present in the biomordants and their ability to interact with the wool's functional groups and dye molecules. The biomordants examined in the study showed unique interactions with the colouring elements of *Butea monosperma* (palas) dye, yielding a variety of shades on wool, including deep brown, olive green, dark brown, cinnamon, burgundy, and yellowish hues. Each biomordant used in the study improved dye performance and produced an array of visually appealing colours with adequate fastness properties. The findings of this research indicate the potential for investigating and utilising additional plant species as sources of biomordants to replace the metallic and harmful mordants currently used in the textile industry.

In their research, Ansari et al. (2021) employed biomordants extracted from *Senegalia catechu* flowers for wool dyeing. This study, however, utilised banana pseudostem sap as a biomordant. The dyeing process incorporated pre, simultaneous, and post mordanting techniques. An assessment of colour strength (K/S Value) was also performed. The colourfastness of the dyed wool was evaluated for washing and light exposure using the Kubelka-Munk equation. Different shades were achieved by varying the dye concentrations. Notably, the simultaneous mordanting technique produced exceptionally high-quality results for the dyed wool samples. While simultaneous mordanting showed promising results, it may not be universally applicable to all types of wool or dye combinations. The study's focus on a single dyeing process could overlook potential drawbacks, such as increased production time

or higher resource consumption, which might outweigh the benefits in some industrial settings. Furthermore, the assessment of color strength and fastness alone may not provide a comprehensive evaluation of the dyed wool's overall quality and durability in real-world applications.

In a study by Hosseinneshad et al. (2020), Iranian madder was employed as an eco-friendly dye, whilst Yellow Myrobalan (YM) and Black Myrobalan (BM) served as biomordants. The presence of appropriate chemical bonds between the wool fibres, green mordant, and dye molecules was confirmed through FTIR-ATR spectra analysis of the washed, mordanted, and mordanted-dyed wool fibres. Enhanced colour strength was observed in wool fibres dyed using a mixture of 4% YM, 6% BM, and 40% madder, as demonstrated by a K/S value of 35.77. This figure substantially exceeded the K/S value of 9.5 obtained for madder by sumac. Furthermore, wool dyed with a combination of YM and BM exhibited favourable fastness properties, including resistance to light, washing, and rubbing.

To maintain biocompatibility in dyeing and address the low affinity of natural dyes, Hosseinneshad et al. (2021) utilized oak as a novel tannin-rich mordant. Using an ultrasound-microwave-assisted extraction in water, yields were approximately 27% for madder, 32% for weld, and 36% for oak. UV-Visible and SEM analyses assessed ash, humidity, and density profiles. The pre-mordanting technique was employed, comparing natural mordants to ferrous sulphate. Analytical protocols examined washed, mordanted, and dyed yarns, ensuring precision. Fastness specifications and colorimetric properties were evaluated, showing dyed yarns performed well and could compete with metal mordants.

Hosseinneshad et al. (2022) used green mordants from yellow and black myrobalan extract with natural dyes madder and resedaluteola. FTIR-ATR spectra of washed, mordanted, and dyed wool yarns verified the bonding of wool with the green mordant and dyes, eliminating C-N peaks through efficient conjugation. Post-dyeing, fastness and dyeing characteristics were examined. Kinetic strength (K/S) values of dyed wool with madder and resedaluteola were measured, and fastness characteristics (light, wash, and rubbing) were determined per ISO standards. The study highlighted myrobalan extraction as a promising method for sustainable manufacturing of dyed spun yarns.

Gong et al. (2020) investigated the potential of utilising natural dye extracted from *Cinnamomum camphora*'s middle-aged/mature leaves for wool colouration. Through the application of various natural mordants, a range of eco-friendly shades with diverse colour spectra, varying in lightness and tone, were produced visually. The study evaluated the effects of different natural mordants (including gallnut, pomegranate peel, arjun bark, chlorophyll extract, and citric acid) and conventional metal mordants (such as ferrous sulfate, copper sulfate, stannous chloride, and sodium dichromate) on the colour and fastness properties of wool samples dyed with 50% (o.w.f.) of *C. camphora* natural dye. The dyeing experiments employed a pre-mordanting technique, with and without mordants. Colour analysis of the dyed wool fibres was conducted using CIELab (L^* , a^* , and b^*) and colour strength (K/S) values. Fastness characteristics were evaluated following ISO standard testing procedures. Generally, wool fibres pre-biomordanted with *P. granatum* (3, 4, and 5% o.w.f.), citric acid (5% o.w.f.), and chlorophyll extract (10–50% o.w.f.) demonstrated comparable colour and fastness results to metal-treated samples. The study also assessed colour durability by examining the impact of washing on the dyed wool fibres. Recent research on wool fabric has focused on sustainable and eco-friendly approaches. Studies have explored natural dyeing with biomordants,

multifunctional treatments, and novel dyeing techniques. Plant-based extracts and biomordants have shown promise in enhancing color attributes, functional properties, and antimicrobial characteristics while providing environmentally friendly alternatives to traditional methods. Natural dyeing with biomordants has gained attention for enhancing color attributes and functional properties. *Terminalia chebula* has shown promise in this regard (Singh and Sheikh, 2020).

Additionally, pomegranate peel, gallnut, and catechu have demonstrated efficacy as natural mordants, offering sustainable alternatives to traditional synthetic mordants in textile dyeing processes (Shahid-ul-Islam et al., 2019). These biomordants provide eco-friendly options for achieving desired color outcomes and improved fabric properties. These promising results open up new avenues for sustainable textile dyeing practices; however, further research is requisite to investigate the scalability and economic feasibility of utilising natural mordants in industrial settings.

Furthermore, Sen et al. (2018) have conducted a comparative analysis of the dyeing process of two regenerated polyester fibres, polytrimethylene terephthalate (PTT) and poly-lactic acid (PLA), in relation to poly-ethylene terephthalate (PET) fibre using natural dyes. Lac was employed as the primary natural pigment, while Catechu was selected as a natural pigment with the additional benefit of functioning as a biomordant. The effects of temperature, initial pH of dye bath, and dyeing time on the colour intensity in the fibres were investigated using Lac and Lac-Catechu combination. The findings indicated that the regenerated polyester fibres exhibited a higher quantity of functional groups and a less dense structure compared to PET. This characteristic facilitated dyeing under less severe conditions. The colour absorption of PTT was significantly greater than that of the other fibres. Moreover, when Lac and Catechu were combined in the same dye bath, an increase in shade intensity was observed for all fibres, suggesting that Catechu functioned as a biomordant. Response Surface Methodology (RSM) was employed to optimise the dyeing of PTT with Lac-Catechu combination using 23-Central Composite Design (CCD). The optimal values for temperature, initial pH, and dyeing time were determined to be 127 °C, 6 minutes, and 26 minutes, respectively. The developed quadratic regression model was deemed statistically significant by ANOVA, with R²-value and adjusted R²-value of 0.9708 and 0.9271, respectively. While the study predominantly focuses on PTT, it also incorporates PET in the comparison, indicating that natural dyeing is feasible for both fibre types, even though potentially with varying degrees of efficacy.

3.4 Bio-Mordants and Its Functional Properties

Safapour et al. (2019) have introduced an environmentally sustainable and economically viable method for dyeing wool and providing it with a durable antibacterial coating using cochineal natural dye. The researchers investigated the potential of a synthetically produced chitosan-cyanuric chloride hybrid (Ch-Cy) to form covalent bonds with wool fibres. They also examined the yarn's dyeing characteristics, colour fastness, and antimicrobial properties. The study involved investigating and optimising key parameters such as Ch-Cy concentration, dye concentration, pH, dyeing duration, and temperature. The findings revealed that treating wool with Ch-Cy (15% on weight of fibre) yielded numerous benefits. These included a significant increase in dye uptake, shorter optimal dyeing time and lower temperature requirements, elimination of metal mordants due to Ch-Cy's bio-mordant properties, and the creation of an antibacterial finish. This finish demonstrated resistance against pathogenic gram-negative

Escherichia coli and gram-positive *Staphylococcus aureus* bacteria for up to 20 wash cycles. The treated wool exhibited satisfactory colour fastness properties within acceptable limits. The researchers concluded that the straightforward Ch-Cy treatment of wool could significantly reduce energy consumption, chemical usage, and dyeing costs. This renders the process more cost-effective and environmentally sustainable compared to conventional methods.

In a related study, Dhanania et al. (2022) explored the use of babul bark (*Acacia nilotica*) extract and gallnut (*Quercus infectoria*) as a bio-mordant for dyeing cotton fabric. The extract contained hydrolyzable tannins, resulting in a light yellow color. When gallnut bio-mordanted cotton was dyed with babul bark extract, a medium to deep brown color was produced due to the formation of a large insoluble colored complex. The researchers fine-tuned the process parameters for extraction, pre-mordanting, and dyeing to establish a standardized dyeing technique. The study also identified dye-bath pH and dye concentration as the paramount dyeing parameters that must be regulated to achieve uniform dyeing. Additionally, the application of gallnut and babul bark resulted in a high UPF value of up to 35, indicating excellent UV protection properties of the dyed cotton. This finding demonstrates the potential for natural dyes and bio-mordants to provide both aesthetic and functional benefits to textile products.

Furthermore, a study by Yaqub et al. (2020) investigated the extraction of an eco-friendly natural dye from red onion (*Allium cepa*) peel using ultrasonic techniques. The extracted dye was applied to silk fabric, both with and without bio-mordants. The researchers used various bio-mordants, including dried tea leaves, tamarind, aloe vera, and acacia bark ash. The investigation focused on assessing colourfastness, colour measurement, and antibacterial properties. The study examined colourfastness in relation to washing, light exposure, heat, rubbing, seawater, and dry-cleaning. Furthermore, the researchers analysed the dyed textiles' colour characteristics using Tristimulus properties (XYZ), Labs values, and Munsell renotations (Hue, Vividness, and Chroma). Additionally, the antibacterial efficacy of the dyed fabrics was tested against three bacterial strains: *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*.

Although various techniques have been studied, further research is needed to optimize and scale up green synthesis methods for improving fabric properties sustainably and commercially. Future studies could focus on optimizing natural dye extraction, developing bio-based finishing agents, investigating synergistic effects between natural compounds, exploring enzymatic treatments, evaluating long-term durability, assessing environmental impact, integrating nanotechnology, and developing scalable industrial processes.

3.5 Bio-Mordants and Its Optimized Conditions

Amin et al. (2020) employed microwave-assisted extraction to obtain colourant from cochineal insects for dyeing silk treated with bio-mordants. The extraction of cochineal natural colourant was performed using acidic, methanolic, and acidified methanol solutions under microwave irradiation for 1 to 6 minutes. The scientists applied optimised conditions to incorporate bio-mordants, thus improving the process's environmental impact and sustainability. The research revealed that an acid-solubilised extract with a pH of 4, applied at 55 °C for 55 minutes, along with 5 g/100 mL of Glauber's salt as an exhausting agent, produced strong colour intensity on microwave-treated silk fabric. According to standardised ISO criteria for colourfastness, bio-

mordants were found to offer superior colour depth and fastness characteristics compared to chemical mordants. The study demonstrated that microwave treatment not only enhanced the dyeing performance of cochineal-derived colourant in an acid-solubilised medium but also improved the colour properties on bio-mordanted silk fibre. While the study shows enhanced color intensity and fastness but does not examine the effects of these treatments on silk fabric's durability, texture, or physical characteristics over time. Future research should investigate whether repeated microwave treatments or bio-mordants impact the silk's structural integrity or longevity compared to traditional dyeing methods. Further exploration of the long-term implications of microwave-assisted extraction and bio-mordants on silk fabric properties is essential to ensure the sustainability and practicality of these innovative dyeing techniques.

Research by Adeel et al. (2021) explored the use of *Peganum harmala* seeds as a natural cotton fabric dye. The study found that microwave extraction and particular dyeing conditions enhanced colour outcomes. The application of chemical mordants, specifically alum (pre-mordant) and iron (post-mordant), intensified colour. Notably, bio-mordants, especially acacia, demonstrated exceptional results. Using 10% acacia as a pre-mordant and 7% as a post-mordant surpassed chemical mordants in colorfastness evaluations. The research underscored the potential of harmala seeds as a natural dye when processed with microwave radiation and utilised with appropriate mordants. This approach offers an environmentally sustainable alternative for the textile industry, maintaining quality and efficacy whilst reducing the ecological impact of fabric production. Optimal results were obtained by exposing the dye extract to radiation, then dyeing untreated fabric under specific conditions: 85 °C for 45 minutes in a dye bath with a pH of 9.0 and a salt concentration of 7 g/100. The increasing demand for eco-friendly textile dyeing processes necessitates the exploration of natural dyes and bio-mordants as alternatives to synthetic dyes and metal mordants. However, the widespread adoption of these natural alternatives is hindered by challenges in achieving comparable colour fastness, intensity, and antibacterial properties to those obtained with conventional methods.

Mahreni et al. (2019) have employed an extract from *B. orellana* seed as a natural dye and an extract from *Centella asiatica* leaves (Pegagan) as a biomordant in the process of cotton textile dyeing. Both raw materials were extracted using water as a solvent. The tannin compounds present in *Centella* leaves have the potential to induce a mordanting effect in cotton. The impact of different concentrations of *Centella* (50, 150, 250 gr/L) and pH levels (4, 6, 8) on the mordanting process (fixation) was investigated and compared together with the use of Alum mordant. Response Surface Methodology (RSM) using Minitab 16 software was employed to optimise the mordanting process. Response Surface Methodology simultaneously identifies optimal conditions for multiple variables, analyses *Centella* concentration and pH effects, reveals interactions, reduces experiments, generates visual plots, provides statistical analysis, and improves the dyeing process.

The colour intensity (K/S), wash fastness, and light fastness properties of each sample were assessed. Functional groups present in the dyed samples were analysed using Fourier Transfer Infra-Red (FTIR). Overall, the addition of *Centella* leaves extract as a mordant has enhanced the wash and light fastness (scale 3 to 3-4) of the dyed sample, while preserving the orange colour characteristic of Bixa, in comparison to the non-mordant sample. The highest colour strength K/S was achieved by mordanting at pH 8, followed by pH 4 and pH 6.

Research by Barahapurkar et al. (2020) explored the bio mordant properties of a natural dye extracted from Celosia flower and banana pseudostem sap when applied to silk textiles. The dyeing process employed three distinct methods: pre-mordanting, post-mordanting, and simultaneous mordanting. The study analysed how dyeing parameters, including mordant concentration, pH, and temperature, influenced dye absorption and fastness properties of the dyed silk for each technique. Optimal dyeing parameters were determined based on maximum dye absorption, measured by K/S values. For all dyeing methods, the ideal mordant concentration was found to be 18%. The most suitable pH levels were 4.5, 4.0, and 4.0, with corresponding dyeing temperatures of 70 °C, 70 °C, and 65 °C for pre-, post-, and simultaneous mordanting techniques, respectively. The dyed silk fabrics underwent colorfastness tests for light exposure, washing, and rubbing. Light and rubbing fastness tests yielded fair-to-good results, while washing fastness was good to very good. The antibacterial properties of silk textiles dyed with banana sap mordants were evaluated, revealing moderate efficacy against both gram-positive and gram-negative bacteria. Overall, the simultaneous mordanting technique exhibited superior performance in terms of dye absorption and fastness characteristics compared to other methods under various dyeing conditions.

The optimisation of bio-mordants with nanoparticles has the potential to enhance textile dyeing efficacy (Aksit et. al., 2017). The combination of bio-mordants with complementary nanoparticles may augment performance. Nanoformulations could potentially improve stability and shelf life. For instance, chitosan nanoparticles loaded with tannin extracts could increase surface area, enhance penetration, control release, and improve stability. This approach may result in superior colour fastness by combining the mordanting effects of chitosan and tannins, potentially enhancing overall dyeing efficiency and reducing waste.

3.6 Comparison of Bio-Mordants and Metal Mordants

Building upon this research, Shahmoradi Ghaheh et al. (2021) assessed the impact of bio-mordants compared to metal mordants on various aspects of color measurement, color fastness, and antibacterial properties of a natural dye extract (*Hibiscus sabdariffa* L.) on cotton fabric. The study examined bio-mordants such as tannic acid, pine cone, lemon peel, and sodium alginate, along with metal mordants including iron(II) sulphate, copper sulphate, zinc sulphate, and aluminium potassium sulphate. Three standard mordanting methods were employed: pre-mordanting, meta-mordanting, and after-mordanting. The results showed that the after-mordanting method was the optimal technique for dyeing *H. sabdariffa* on cotton fabric based on the color fastness factor. Interestingly, the bio-mordants used in this study, similar to metal salts, enhanced the color fastness of the dyed cotton fabrics and yielded exceptional light fastness, wash fastness, and dry/wet rub fastness. Furthermore, tannic acid, pine cone, and lemon peel exhibited superior antibacterial effects against *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa* when applied to the dyed cotton fabric. Nahar et al. (2020) explored the use of Eucalyptus leaves as a natural dye source for jute fabric, employing common mordants whilst optimising dyeing parameters. The dye was extracted from Eucalyptus leaves using hot water. The fabric underwent pre-mordanting with various synthetic agents, including alum, potassium dichromate, copper sulphate, and ferrous sulphate, before dyeing. These mordants are typically used to enhance the dyestuff's intensity on textiles and improve fastness properties. Synthetic mordants were chosen over natural ones due to their better compatibility with jute fabric and Eucalyptus leaves during dyeing, as natural mordants

have limited impact on jute. Another aim of the study was to reduce time and energy consumption in the jute dyeing process, resulting in a dyeing temperature of 75 °C for approximately 30 minutes. Assessments were conducted through visual inspection, examining colour-coordinate values and colour intensity. Colour fastness was evaluated using tests for water immersion, washing, rubbing, and perspiration. The dyeing technique produced colours ranging from yellowish to brown when different mordants were applied. Superior results were achieved with ferrous sulphate pre-treatment, as evidenced by precise colour coordinate and colour strength values. Jute fabric dyed solely with Eucalyptus extract showed satisfactory results across all colour fastness tests. Fabrics treated with various mordants exhibited differing fastness ratings, with ferrous sulphate and copper sulphate treatments yielding slightly better fastness results. Expanding upon the encouraging outcomes of bio-mordants in eco-friendly textile dyeing, scientists have also delved into novel uses for banana fibre.

3.7 Exploring Biomordants from Agricultural By-Products

Agricultural waste, such as banana pseudo stem waste, presents innovative opportunities for sustainable dyeing in the textile industry. Utilizing these by-products reduces environmental impact, adds value to waste materials, and potentially creates new markets for eco-friendly fashion. Investigating other agricultural waste as biomordants could yield diverse, sustainable colors and textures. Biomordants promote a circular economy model, maximizing resource efficiency while addressing environmental concerns and creating economic opportunities. The resulting products demonstrate enhanced sustainability, reduced environmental impact, and improved performance. Recent research has explored innovative applications for banana pseudo-stems, including paper production and nanoparticle synthesis. Assessing the chemical composition and diverse uses of this abundant resource emphasizes the economic and environmental advantages of repurposing agricultural waste in sustainable technologies.

Cordeiro et al. (2004) conducted an investigation into the chemical makeup and pulping potential of banana pseudo-stems grown on Madeira Island, Portugal. Their research sought to assess the suitability of *M. acuminata* Colla as a viable source of lignocellulosic fibres for paper and composite production. The study examined the raw material in its entirety (type I) and separately analysed the outer bark portion (type II), which contains a higher concentration of cellulose fibres. Before initiating the cooking process of banana waste, the researchers measured the primary components of both material types. The findings revealed a sufficiently high polysaccharide content (approximately 60–70%) to justify pulping evaluations, along with a notably low lignin content of around 12%. The only concerning discovery was the relatively high levels of ashes and extractives. The researchers employed soda, kraft, and soda-anthraquinone (AQ) cooking methods to pulp these residues and determined the optimal pulping parameters. The results showed that pulps with a yield of about 37-38% and a Kappa number (Kappa no.) of roughly 30-32% could be produced when cooked at 120 °C for a short period of 30 minutes with 0.25-0.35% anthraquinone. Extending cooking times and raising temperatures, as well as utilising kraft pulping conditions, did not yield better outcomes compared to the aforementioned conditions. These more extreme conditions negatively impacted the preservation of hemicellulose.

Investigating other agricultural waste as biomordants could yield diverse, sustainable colors and textures. This promotes a circular economy model, maximizing resource efficiency while addressing environmental concerns and creating economic opportunities. The resulting

products demonstrate enhanced sustainability, reduced environmental impact, and improved performance. This review paper has comprehensively discussed the recent researches and has focused on innovative applications for banana pseudo-stems, including paper production and nanoparticle synthesis. Assessing the chemical composition and diverse uses of this abundant resource emphasizes the economic and environmental advantages of repurposing agricultural waste in sustainable technologies.

Building upon the promising results of utilising banana pseudostem as a bio-mordant, researchers have commenced exploring the integration of green nanosynthesis techniques to further enhance the sustainability and functionality of textile dyeing processes using this abundant agricultural waste product, which is further discussed below.

3.8 Impact of Nanotechnology in Bio-Mordanting & Natural Dyeing

In a research approach by Yu et al., 2019, involved dyeing white cotton fabric with natural dye extracted from black rice while simultaneously incorporating silver nanoparticles onto the fabric surface. Black rice extract served as both a natural dye and a reducing agent, facilitating the reduction of silver ions in solution to form silver nanoparticles. These nanoparticles subsequently adhered to the cotton fabric, imparting both colour and antibacterial properties. The process was conducted in a single bath, promoting efficiency and environmental sustainability. The researchers investigated the effects of various pH levels on the colour and other properties of the treated fabric. Initially, the fabric was immersed in a silver nitrate solution, followed by treatment with black rice extract. Although the researchers did not explicitly mention the use of metal-ion mordants, the fabric was pretreated with a silver solution prior to the application of the dye extract. The study yielded several significant findings. The researchers ascertained that this method successfully produced AgNPs that were uniformly distributed on the fabric surface. The pH level of the synthesis bath significantly influenced the colour and colour strength of the treated fabric, with a pH of 10 resulting in the optimal colour strength, washing fastness, and UV protection. The treated fabric demonstrated considerable antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*, with over 80% antibacterial activity retained even after 25 washes. Additionally, the fabric demonstrated excellent UV protection capabilities, attributed to two primary factors: the black rice extract's strong UV absorption, particularly around the 290 nm wavelength, and the silver nanoparticles blocking UV penetration. The fabric treated at a pH of 10 exhibited the highest UPF value and lowest UV transmittance, indicating superior UV protection (Yu et al., 2019).

Deena et al. (2015) described an eco-friendly method for producing silver nanoparticles using banana sap, which served as a solvent, reducing agent, and capping agent. The researchers also utilised banana sap to bind silver nanoparticles to cotton fabric. The formation of silver nanoparticles was monitored quantitatively using UV-Visible spectroscopy, with the characteristic surface plasmon absorption peaks observed at 418-425 nm confirming their presence. The silver nanoparticle-coated fabric demonstrated significant antibacterial properties against both gram-negative bacteria (*Pseudomonas aureginosa* and *Escherichia coli*) and gram-positive bacteria (*Bacillus subtilis* and *Staphylococcus aureus*).

In a related study, Doan et al. (2020) synthesised silver nanoparticles (AgNPs) and gold nanoparticles (AuNPs) using an aqueous extract from waste banana stem (WBS) of *Musa*

paradisiaca Lenn. The researchers employed various analytical techniques, including X-ray diffraction (XRD), Fourier transmission infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and transmission electron microscopy (TEM), to characterise the reduction and formation of these metallic nanoparticles (MNPs). The analysis revealed that the average particle sizes of WBS-AgNPs and WBS-AuNPs in their crystalline state were 7-13 nm and 11-14 nm, respectively. The synthesised nanoparticles were evaluated for their antibacterial and catalytic properties. WBS-AgNPs exhibited strong antibacterial activity against *Bacillus subtilis* and *Escherichia coli*, with the largest inhibition zones observed at concentrations of 4.0 ppm (14.2 mm) for *B. subtilis* and 2.0 ppm (9.3 mm) for *E. coli*. Both nanoparticles demonstrated remarkable catalytic activity in reducing 4-nitrophenol, with normalised kinetic constants (k_{nor}) of $1.72 \times 10^{-3} \text{ s}^{-1} \text{ mg}^{-1}$ for WBS-AgNPs and $2.45 \times 10^{-3} \text{ s}^{-1} \text{ mg}^{-1}$ for WBS-AuNPs. The researchers concluded that this method offers an efficient, environmentally friendly, cost-effective, and straightforward approach for producing metallic nanoparticles with potential applications in wastewater treatment and pharmaceuticals. The technique utilises agricultural waste materials and avoids the use of hazardous chemicals, with the bioactive compounds in the waste banana stem extract acting as both capping and reducing agents in the conversion of metallic ions to nanoparticles. The sap from banana pseudo-stems serves as a highly effective biomordant in natural dyeing processes. Silk fabrics dyed using this method demonstrate high dye uptake and excellent fastness ratings across various dyeing conditions and techniques.

Despite these advancements, research gaps in bio-mordants and sustainable textile dyeing encompass several key areas. The limited industrial-scale application hinders widespread adoption, while the lack of standardized protocols impedes consistent results. Additionally, incomplete understanding of mordanting mechanisms restricts optimization efforts, and the narrow focus on natural fibers overlooks potential applications in synthetic textiles.

Building on the advancements and challenges discussed above, recent studies have demonstrated that nanoparticles can significantly enhance the effectiveness of natural dyeing processes. For example, it is clearly observed in the above studies that used banana sap to produce silver nanoparticles and coat cotton fabric, resulting in antibacterial properties against both gram-negative and gram-positive bacteria.

Furthermore, insufficient data on long-term stability and durability of bio-mordanted textiles raises concerns about product longevity. To address these challenges and move the field forward, comprehensive studies are needed to develop scalable processes, establish standardized methods, elucidate mordanting mechanisms, explore applications in diverse fiber types, and assess the long-term performance of bio-mordanted textiles. Such research would significantly advance sustainable textile dyeing practices. The limited research may result in significant knowledge gaps, making it difficult for researchers and industry professionals to build upon existing work and advance the field. By systematically addressing these research gaps, the textile industry can make significant strides towards more environmentally friendly dyeing processes.

4. Critical Insights and Synthetic Analysis of the Literature

Thematic Interpretation

4.1 Sustainable alternatives to metal mordants:

- Bio-mordants: Plant based biomordants show comparable or better performance to metal mordants in enhancing color fastness and intensity.
- Natural tannin-rich plant extracts performed similar to alum in terms of color difference and wash fastness.
- Bio-mordants produced a range of color shades and improved overall dyeing sustainability.

Bio-mordants derived from plants like *Terminalia chebula*, pomegranate peel, gallnut, and catechu have demonstrated comparable or superior performance to metal mordants in enhancing color fastness and intensity. Natural tannin-rich plant extracts, such as those from *Rhus coriaria* and *Eucalyptus*, have shown similar effectiveness to alum in terms of color difference and wash fastness. These bio-mordants not only produce a variety of color shades but also improve certain aspects of the dyeing process. The use of these sustainable alternatives addresses environmental concerns associated with traditional metal mordants while maintaining or enhancing the quality of dyed textiles.

Thematic Interpretation

4.2 Comparative analysis of bio-mordants vs. metal mordants:

- Bio-mordants showed comparable or better performance to metal mordants in enhancing color fastness and intensity.
- Natural tannin-rich plant extracts performed similarly to alum in terms of color difference and wash fastness.

Biomordants and metal ions serve as mordants in textile dyeing, but differ in their origins and environmental impact. Biomordants, derived from natural sources like pomegranate peel and gallnut, offer an eco-friendly alternative to traditional metal mordants. They contain tannins and other organic compounds that interact with fiber and dye molecules, enhancing color fastness and intensity. Metal ion mordants, such as alum or copper sulfate, are inorganic compounds that form strong bonds between dye and fiber. While effective, they can be environmentally harmful. Biomordants produce varied shades and often yield comparable or superior results to metal mordants in terms of color fastness and intensity. The use of biomordants aligns with sustainable practices in the textile industry, reducing reliance on potentially toxic metal salts. optimization techniques for natural dyeing processes. Moreover, Nanoparticle-enhanced bio-mordants could potentially enhance dye uptake and colour fastness through increased surface area and reactivity. Nano-encapsulation of bio-mordants may facilitate improved stability and controlled release during the dyeing process.

Thematic Interpretation

4.3 Optimization of extraction and application techniques:

- Microwave-assisted extraction improved dyeing performance of natural dyes and bio-mordants.
- Optimal dyeing conditions were identified for various bio-mordants (e.g. temperature, pH, concentration).

Optimization refers to the process of finding the best possible solution to a problem or system within given constraints. In the context of natural dyeing processes, optimization involves:

- 1) Identifying key dyeing parameters
- 2) Minimizing resources use
- 3) Impactful results with improved dyeing process
- 4) Adapting new raw materials
- 5) Innovative and sustainable approach

In this review paper, Microwave-assisted extraction is highlighted as an efficient method for obtaining natural dyes and bio-mordants, improving dyeing performance. The study identified optimal dyeing conditions for various bio-mordants, with temperature being one of the parameters considered. This holistic approach to enhancing natural dyeing processes suggests a focus on sustainable and eco-friendly practices in textile dyeing. The research likely aims to improve color intensity, fastness, and overall quality of naturally dyed textiles while minimizing environmental impact.

Thematic Interpretation

4.4 Multifunctional properties of bio-mordants:

- Impart antibacterial properties through various mechanisms
- Make fabrics suitable for high-hygiene applications
- Offer notable UV protection, as measured by ultraviolet protection factor
- Contribute to more sustainable multifunctional fabrics

Bio-mordants, derived from sources like oak and pomegranate peel, enhance color attributes and fastness while providing a sustainable alternative to synthetic dyes and metal mordants. Advanced extraction techniques improve dye yields, and pre-mordanting with natural mordants achieves comparable results to metal mordants. Notably, bio-mordanted fabrics exhibit antibacterial properties, making them suitable for applications requiring high hygiene standards. The antibacterial action of these fabrics is multifaceted, involving surface protection, release of antimicrobial compounds, and alteration of fabric surface chemistry. These properties contribute to reduced microbial contamination and odor formation, enhancing the performance and longevity of bio-mordanted textiles.

In addition to this, the UV protective properties of bio-mordanted and naturally dyed fabrics. Studies have shown that these treatments significantly enhance UV protection, as measured by ultraviolet protection factor (UPF) values. The mechanism involves strong UV absorption by natural dye extracts, nanoparticles blocking UV penetration, and the formation of insoluble colored complexes. Factors influencing UV protection include the type of bio-mordant, dye source, and pH level. Notably, these treatments often provide multifunctional benefits, such as antimicrobial activity, alongside UV protection. This eco-friendly approach offers a promising method for producing functional and protective textiles, though further research is needed to fully understand the underlying mechanisms.

Thematic Interpretation

4.5 Use of banana pseudostem:

- Banana pseudostem sap was effective as a bio-mordant, with simultaneous mordanting technique producing high quality results.
- Banana pseudostem sap as a bio-mordant resulted in high dye absorption and excellent color properties.

Banana Pseudostem as Biomordant Agricultural waste, particularly banana pseudo-stem waste, offers sustainable dyeing opportunities in textiles. Research has explored innovative applications through nanoparticle synthesis. Banana pseudo-stem sap serves as an effective biomordant, enhancing dye uptake and fastness in silk fabrics. Studies have investigated optimal dyeing parameters and techniques. The resulting textiles show improved sustainability, reduced environmental impact, and antibacterial properties. This approach promotes a circular economy, maximizing resource efficiency while addressing environmental concerns. However, challenges remain in scaling up processes, standardizing methods, and understanding long-term stability, necessitating further research to advance sustainable textile dyeing practices. Future research should prioritize innovative, eco-friendly nanoparticle synthesis methods. Emphasis should be on sustainable production using renewable resources to minimize environmental impact. Plant extracts as reducing and capping agents present a cost-effective, non-toxic alternative to traditional methods. Furthermore, exploring microorganisms and biomolecules in nanoparticle synthesis could yield scalable processes that adhere to green chemistry principles.

Thematic Interpretation

4.6 Nanotechnology-Driven Progress in use of Biomordants and Natural Dyeing Process

- Green synthesis of nanoparticles
- Multifunctional properties
- Optimisation of Nanoparticles
- Characterisation techniques
- Durability of functional properties

The green synthesis of nanoparticles using natural extracts like black rice and banana sap offers an environmentally friendly and cost-effective alternative to traditional methods. These extracts serve as reducing and capping agents for silver and gold nanoparticles, eliminating the need for harmful chemicals. The resulting nanoparticles impart multiple functional properties to fabrics, including coloration, antibacterial activity, and UV protection. Process optimization, particularly pH control, significantly influences the performance of treated fabrics. Various analytical techniques confirm nanoparticle formation and characterize their properties, with green synthesis methods yielding controlled particle sizes. Both silver and gold nanoparticles demonstrate catalytic activity, suggesting potential applications in wastewater treatment. The durability of functional properties, such as antibacterial activity, is retained after multiple wash cycles. Natural extracts like banana sap serve multiple functions in the synthesis and dyeing processes, showcasing the versatility of these sustainable

resources. This approach not only utilizes agricultural waste but also enhances textile properties, including color fastness and UV protection, demonstrating the potential for eco-friendly advancements in nanotechnology and textile manufacturing.

Thematic Interpretation

4.7 Research Gaps

- Limited industrial-scale application of nanosynthesis of bio-mordants
- Lack of standardized protocols for bio-mordant use
- Incomplete understanding of bio-mordanting mechanisms
- Insufficient data on the long-term stability of bio-mordanted textiles

This review identifies significant research gaps in bio-mordants and sustainable textile dyeing, such as limited industrial-scale applications, lack of standardized protocols, incomplete understanding of mordanting mechanisms, narrow focus on natural fibers, and insufficient data on long-term stability. The promising nature of nanosynthesis for bio-mordant development suggests that valuable opportunities for sustainable textile dyeing are not being fully explored or realized. Future research should emphasize scaling up bio-mordant production, developing standardized protocols, studying chemical mechanisms, and expanding research to include synthetic fibers. These efforts will advance sustainable textile dyeing and promote wider adoption of bio-mordants in industry, reducing the ecological footprint and improving sustainability.

Key conflicting findings include:

1. Effectiveness compared to metal mordants:

While many studies suggest bio-mordants are comparable or superior to metal mordants in color fastness and intensity, debate persists about their efficacy across all applications and fiber types. More research is needed to demonstrate their effectiveness conclusively.

2. Scalability and standardization:

The review points out limited industrial-scale applications and lack of standardized protocols. Conflicting views may exist on the feasibility of scaling up bio-mordant production to industrial levels and achieving standardization given the variability of natural materials.

3. Optimal extraction and application methods:

Studies have employed various extraction techniques (e.g., microwave-assisted, ultrasonic) and application methods (e.g., pre-mordanting, simultaneous mordanting), leading to conflicting findings on optimal approaches for different bio-mordants and fabrics.

4. Long-term stability:

There is insufficient data on the long-term stability of bio-mordanted textiles. While some studies indicate good durability of properties like antibacterial activity, comprehensive long-term testing is needed to resolve potential conflicting results.

5. Mechanisms of action:

The exact mordanting mechanisms of different bio-mordants remain incompletely understood, and studies have not thoroughly discussed how bio-mordants interact with fibers and dyes at the molecular level.

It is recommended to incorporate more comprehensive research on the application of nanotechnology in bio-mordant optimisation, extraction, and application methodologies. Research should focus on novel techniques for examples, nanocellulose as a bio-mordant carrier, nano-emulsions for bio-mordant application, improving dispersion and fibre interaction, and nanotechnology in extraction optimisation for improved extraction efficiency from plant sources.

Overall, while the review suggests strong potential for bio-mordants, it also highlights areas where further research is needed to resolve conflicting findings or interpretations and conclusively demonstrate their effectiveness across a wide range of applications. The field appears to be evolving rapidly, with new bio-mordant sources and techniques constantly emerging.

5. Conclusion

The review indicates that bio-mordants offer a sustainable alternative to traditional metal mordants in textile dyeing, providing comparable or better color fastness and intensity while minimizing environmental impact. Bio-mordanted fabrics possess multifunctional properties, such as antimicrobial activity and UV protection, which enhance product value. However, further research is necessary to fully integrate bio-mordants into industrial applications. This includes scaling up processes, standardizing methods, understanding mordanting mechanisms, and assessing long-term performance. Nanosynthesis of bio-mordants represents a promising advancement in natural dyeing, offering improved color fastness and intensity across various fabrics while promoting sustainability. This approach not only enhances the dyeing process but also adds functional properties to textiles, thereby increasing their value and versatility.

Addressing these challenges systematically can significantly advance sustainable dyeing in the textile industry. Utilizing agricultural waste, such as banana pseudostem, as a bio-mordant source demonstrates the potential for a circular economy in textile production, reducing environmental impact, adding value to waste materials, and creating new economic opportunities. Although bio-mordants and sustainable dyeing show promise, ongoing research and development are crucial to overcoming current limitations and achieving widespread adoption. Research areas include scaling up industrial applications, standardization, understanding mordanting mechanisms, expanding fiber types, assessing long-term stability, exploring novel sources, combining with other sustainable technologies, enhancing functional properties, and conducting comprehensive environmental impact assessments.

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