

## Review

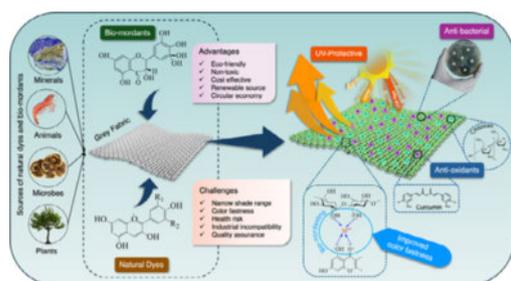
# Toward a Greener Fabric: Innovations in Natural Dyes and Biomordants for Sustainable Textile Applications

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## GRAPHICAL ABSTRACT



## ABSTRACT

The textile industry has historically shifted from natural to synthetic dyes and mordants due to factors such as broader color range, improved colorfastness, and large-scale production efficiency. However, synthetic alternatives raise serious environmental and health concerns owing to their toxicity, nonbiodegradability, and resource-intensive manufacturing. With increasing global emphasis on sustainable and eco-conscious practices, there is renewed interest in natural dyes and biomordants. This review critically examines the resurgence of these bio-based colorants, comparing traditional natural dyes and mordants to modern innovations in terms of performance, environmental impact, and feasibility for industrial use. While natural dyes offer biodegradability and reduced toxicity, they face limitations in color consistency, fastness, and scalability. Advances in biotechnology have led to the development of bioengineered dyes from microorganisms, waste-derived pigments, and biomordants such as chitosan, tannins, and enzymes that address some of these challenges. Additionally, hybrid approaches incorporating nanotechnology are enhancing dye uptake and durability. By integrating insights from materials science and green chemistry, this review outlines the current state and future prospects of natural dyes and biomordants in transforming textile manufacturing into a more sustainable industry.

**Keywords** Natural dyes, Biomordants, Sustainable textiles, Eco-friendly dyeing, Bioengineered pigments, Nanotechnology in dyeing

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## Significance

This review critically compares natural and synthetic dyes in terms of environmental impact, colorfastness, chemical structure, and application in sustainable textiles. By highlighting eco-friendly

alternatives and evaluating their performance, the article supports circular design and responsible consumption. It contributes to SDG 12 by promoting sustainable practices in the dyeing industry and guiding future research and industrial adaptation.

## 1 Introduction

### 1.1 Sustainable Textile Dyeing: Context and Importance

Textile dyeing is among the most chemically intensive processes in the global manufacturing industry. Although synthetic dyes dominate industrial practices due to their wide color range, ease of application, and high reproducibility, they are increasingly criticized for their adverse environmental and health impacts, including carcinogenicity, toxic sludge generation, and severe water pollution.<sup>1–3</sup> These concerns have accelerated the global push toward greener fabrics, circular economy models, and eco-friendly dyeing practices that minimize environmental footprints and promote sustainable development.<sup>4–6</sup>

Within this context, natural dyes—colorants derived from plants, animals, insects, fungi, algae, and minerals—have re-emerged as viable alternatives. Historically, they were the primary source of textile coloration, offering diverse hues from roots, stems, seeds, flowers, fruits, bark, and leaves.<sup>7–9</sup> Their advantages include biodegradability, low toxicity, renewable sourcing, and potential biofunctional properties such as antimicrobial and antioxidant activity.<sup>10–12</sup> However, natural dyes face limitations such as shade variability, poor reproducibility, and lower fastness compared to synthetic dyes.<sup>13</sup> In addition, issues of pigment stability and extraction efficiency remain challenges, although recent innovations in pretreatment and extraction technologies have begun to address these barriers.<sup>14,15</sup>

To overcome these challenges, mordants play a critical role. Mordants are substances that enhance dye–fiber interactions, improve color fastness, and sometimes impart additional functionalities.<sup>16</sup> While conventional metallic mordants (chromium, copper, iron, tin, etc.) are effective, they raise serious ecological and health concerns due to heavy metal contamination.<sup>17–19</sup> This has motivated growing interest in biomordants derived from tannins, chitosan, enzymes, and agricultural by-products, which can achieve dye fixation with reduced toxicity.<sup>20–22</sup> Some biomordants also introduce multifunctional benefits, such as antimicrobial activity or UV protection, thereby aligning dyeing practices with broader sustainable textile innovation.<sup>23,24</sup>

It is important to note that dyes and mordants serve fundamentally different roles: dyes act as coloring agents, whereas mordants are auxiliary chemicals that strengthen bonding between the dye and the fiber. Natural dyes are often described as having “minimal reactivity,” meaning they do not readily release harmful by-products or chemically degrade fibers during processing. Yet this advantage is also a drawback, as weaker binding necessitates the use of mordants to ensure adequate shade depth, retention, and durability.<sup>13,20</sup>

Thus, natural dyes and biomordants together represent a crucial frontier in sustainable textile dyeing—one that not only addresses long-standing environmental and health concerns but also aligns with the principles of the circular economy, eco-innovation, and emerging nanotechnology-enabled solutions for greener fabric production.<sup>14,15</sup>

### 1.2 Challenges, Gaps in Literature, and Justification for This Review

Despite the increasing recognition of their ecological and functional advantages, natural dyeing and biomordant systems still

face numerous technical, economic, and scalability challenges that restrict their industrial uptake. A key challenge is the limited color palette and shade reproducibility offered by natural dyes compared to the vast range and high consistency of synthetic dyes.<sup>13</sup> Seasonal and geographic variations in natural dye sources also create inconsistencies in availability, extraction yield, and quality, making standardization difficult.<sup>14,15</sup>

In terms of performance, natural dyes typically exhibit poor light, wash, and rubbing fastness unless mordants are employed to strengthen dye–fiber interactions. However, many processes still rely on toxic metallic mordants such as chromium, tin, and copper salts, which compromise the environmental benefits of natural dyeing.<sup>16</sup> The higher costs, time-intensive extraction processes, and lack of efficient large-scale processing methods further hinder commercialization.<sup>23,24</sup>

From a research standpoint, several key gaps remain unaddressed. Existing studies have often focused on individual dye types or isolated mordanting methods rather than providing a comparative and systematic framework. Critical mechanisms of dye–fiber–mordant interactions remain underexplored, particularly in terms of molecular modeling and computational insights. Moreover, while new directions such as microbial pigments, waste-derived dyes, and nanotechnology-assisted biomordants are emerging, the literature is fragmented and lacks integration.<sup>13,16</sup> Similarly, the multifunctional properties of natural dye–biomordant systems—such as antimicrobial, UV-protective, and antioxidant functionalities—have not been adequately reviewed in relation to advanced textile sectors like medical fabrics, active-wear, and protective clothing.<sup>4</sup>

The problem is thus twofold: on the one hand, industries are under mounting pressure to adopt greener dyeing systems that reduce pollution and align with circular economy principles; on the other, researchers and practitioners lack a comprehensive and structured resource that synthesizes current advances, identifies shortcomings, and charts out directions for scalable solutions.

Therefore, this review aims to fill these gaps by (i) systematically comparing natural dyes and biomordants, (ii) analyzing their fixation mechanisms and environmental implications, (iii) assessing value-added functionalities for advanced textiles, and (iv) highlighting future opportunities such as nanotechnology, enzyme-based mordants, and microbial dyeing. By addressing these critical issues, this article contributes both to academic knowledge and to practical pathways for sustainable textile coloration.

### 1.3 Methodology of Literature Selection

To ensure comprehensive coverage, we followed a structured methodology for selecting articles included in this review. Research articles and reviews were sourced from Scopus, Web of Science, Google Scholar, and ScienceDirect databases. Keywords used included: “natural dyes,” “bio-mordants,” “green dyeing,” “textile sustainability,” “nanotechnology in dyeing,” “chitosan mordant,” “tannin mordant,” “UV protection textiles,” and “microbial pigments.” Preference was given to publications from 2010 to 2024, with particular focus on recent studies from the last five years that address functional properties, dye–mordant interactions, and sustainability metrics. Articles were screened based on relevance, citation impact, and contribution to the objectives of this review.

## 1.4 Rationale and Objectives

The growing interest in sustainable textiles has drawn attention to natural dyes and biomordants as viable alternatives to synthetic and metallic agents. However, several critical gaps persist in the current literature, which justify the need for a comprehensive and integrative review. There remains a lack of holistic understanding regarding the interactions between natural dyes and biomordants, especially in relation to their functional performance and sustainability. Comparative insights into traditional versus emerging mordanting systems, as well as their mechanisms of action, are also limited. Furthermore, regulatory concerns and environmental pressures have created an urgent demand for safer and eco-compatible alternatives to metal-based mordants. While biotechnology, materials science, and green chemistry are advancing rapidly, these developments often remain fragmented across disciplines, making it difficult to form a cohesive perspective.

In response to these challenges, this review aims to offer a structured and interdisciplinary examination of natural dyeing systems. Specifically, the objectives include the classification of natural dyes and biomordants based on their sources, chemical structures, and functionalities. It also seeks to elucidate the mechanisms underlying dye fixation and the molecular interactions between dyes, mordants, and textile fibers. In addition, the review assesses the value-added properties imparted by these natural systems—such as antibacterial, antioxidant, and UV-protective effects—which contribute to their appeal in functional textiles. Innovations in the field, including microbial dyes, enzyme-assisted mordanting, nanotechnology applications, and the use of waste-derived pigments, are highlighted to showcase the breadth of recent progress. Lastly, the study proposes future research directions that emphasize scalable, eco-friendly dyeing methods aligned with the principles of green chemistry and the circular economy.

## 2 Classification and Applications of Natural Dyes

Natural dyes have garnered renewed interest in recent years due to their biodegradable, nontoxic, and renewable nature. Their use in textiles and other industries aligns with the global shift toward eco-friendly materials and sustainable processes. These dyes are generally categorized based on chemical structure, source, and application areas. A clear understanding of these classifications not only enhances our scientific knowledge but also helps identify specific dye types suitable for targeted applications such as antibacterial textiles, UV-protective clothing, cosmetic formulations, and food-grade colorants.<sup>17</sup>

### 2.1 Classification Based on Chemical Structure

The chemical structure of a natural dye determines its color, solubility, interaction with mordants, and functional properties on textiles. Quinonoids provide vivid red and yellow hues and are primarily found in plants like madder (*Rubia tinctorum*) and henna (*Lawsonia inermis*). Flavonoids known for their yellow to orange tones are abundant in weld (*Reseda luteola*) and pomegranate

(*Punica granatum*). Anthocyanins are water-soluble pigments which produce a range of red, blue, and purple hues found in grapes, hibiscus, and berries. Tannins are often classified as mordants due to their metal-binding properties; tannins also impart color, especially those from sources like gallnuts, myrobalan, and tea. Carotenoids are responsible for vibrant yellow to orange colors; they are derived from marigold (*Tagetes*), saffron, and carrots. These dye classes not only differ in hue but also in their binding affinities, stability, and reactivity with various fibers. Their antioxidant and antimicrobial potential have been demonstrated in recent studies, further supporting their utility in functional textiles.<sup>17,18</sup> The chemical structures of common classes of natural dyes are presented in Fig. 1.

### 2.2 Classification Based on Source

The classification of natural dyes based on their origin provides insights into their chemical characteristics, extraction techniques, and ecological advantages. The largest group of natural dyes is plant-based, derived from various parts of plants including leaves, roots, bark, seeds, flowers, and fruits. Common examples include indigo extracted from *Indigofera tinctoria*, alizarin obtained from madder roots, and curcumin sourced from turmeric (*Curcuma longa*). These dyes are extensively used in the textile, cosmetic, and food industries owing to their biodegradability, low toxicity, and functional bioactive properties.<sup>5,6</sup>

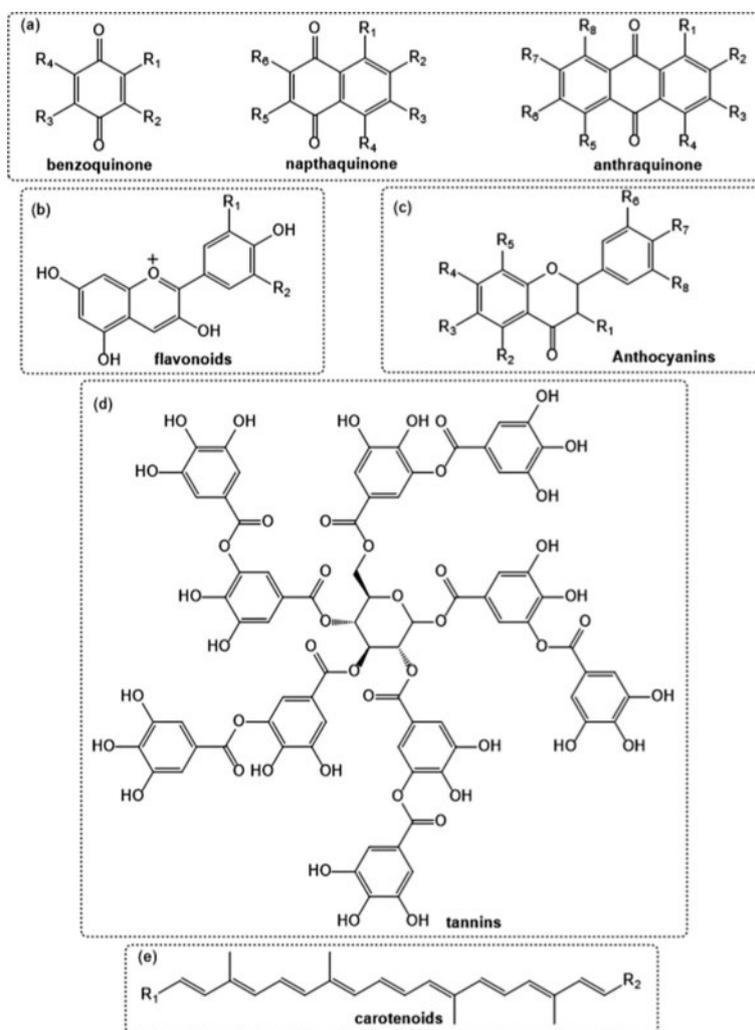
Research has confirmed that dyes derived from turmeric and pomegranate exhibit antibacterial, antioxidant, and UV-protective effects,<sup>19,20</sup> further enhancing their value for sustainable applications.

Animal-based dyes are obtained from insect or marine sources. Notable examples include carmine red extracted from cochineal insects (*Dactylopius coccus*), lac dye from *Kerria lacca*, and the historically prized Tyrian purple derived from mollusks. These dyes are especially valued in high-end textile and cosmetic applications due to their vivid color strength (tinctorial power) and excellent fastness to light and washing.<sup>21–24</sup>

Another category includes mineral-based dyes, which are sourced from naturally occurring mineral deposits. Ultramarine, originally obtained from lapis lazuli, along with ochre and iron buff, are traditional examples. These dyes are well known for their stability and high lightfastness, making them suitable for use not only in textiles but also in the conservation of historical artworks.<sup>25,26</sup>

Natural pigments can also be obtained from microbial and fungal sources, particularly through fermentation processes. Certain bacteria and fungi are capable of producing highly pigmented compounds under controlled conditions. For instance, *Serratia marcescens* produces the red pigment prodigiosin, while *Monascus purpureus* yields a range of red hues. These microbial dyes offer advantages such as biocompatibility, consistent production, and independence from agricultural land, making them suitable for scalable and sustainable industrial use.<sup>27–29</sup>

Lastly, lichen and mushroom-derived dyes have a long history, especially in traditional European and Asian dyeing practices. An example is orchil, a violet dye obtained from certain lichen species. Although these sources are less commonly used in contemporary large-scale production, they hold significant



**Fig. 1** Chemical sources of natural dyes: (a) Structural classes—anthraquinone, (b) flavonoids, (c) anthocyanins, (d) tannins, and (e) carotenoids.

ethnobotanical and artisanal value, especially in the context of cultural heritage and natural dye craftsmanship.<sup>30</sup>

This diversity in sources allows for multifunctional dyeing applications, and many of these have been shown to be eco-friendly and nontoxic through toxicity assays, cytotoxicity evaluations, and biodegradability tests.<sup>31</sup> The various sources of natural dyes are presented in **Fig. 2**.

## 2.3 Applications of Natural Dyes in Textile and Allied Industries

Natural dyes are increasingly applied beyond traditional textile coloration, supported by their biodegradability, absence of toxic heavy metals, low allergenic potential, and in some cases, added biofunctional properties. These eco-friendly and nontoxic attributes are not only based on historical use but also supported by contemporary research and international regulatory approvals.

### 2.3.1 Textile Industry

Natural dyes are widely used for cotton, wool, silk, and their blends, where they can impart antimicrobial, UV-protective, and

antioxidant functionalities.<sup>32</sup> For example, curcumin- and tannin-treated fabrics inhibit bacterial growth and absorb UV radiation.<sup>33</sup> Their eco-safety is reinforced by the fact that most natural dyes do not release toxic aromatic amines during degradation, unlike azo-based synthetics.<sup>4,15</sup>

### 2.3.2 Cosmetics

Pigments such as cochineal (carmine), turmeric, and anthocyanins are used in lipsticks, foundations, and skin-care formulations owing to their stability, antioxidant properties, and low incidence of skin irritation compared to synthetic colorants. Many of these pigments are approved by the US FDA and the EU Cosmetic Directive, confirming their safety for dermal application.<sup>34–36</sup>

### 2.3.3 Food and Beverages

Colorants like carotenoids, betalains, and anthocyanins are widely employed in juices, confectionery, dairy, and plant-based meats. Their eco-safety derives from their natural metabolic pathways in humans, with several classified as Generally Recognized as



**Fig. 2** Exploring the origins of natural dyes: a spectrum of colors from plants, minerals, microbes, and animals.

Safe (GRAS) by the FDA.<sup>37,38</sup> Moreover, many provide nutritional benefits beyond color, such as antioxidant activity, pro-vitamin A activity (carotenoids), and cardiovascular health support.<sup>39</sup>

### 2.3.4 Heritage Conservation and Art

Natural dyes derived from minerals, plants, and insects are used in conservation of textiles, manuscripts, and wall paintings because of their chemical compatibility with historical substrates and long-term stability.<sup>40</sup> For instance, indigo, madder, and cochineal are frequently reapplied in museum restoration projects as they replicate the authenticity of ancient materials without introducing harmful residues.<sup>41</sup>

By categorizing natural dyes through these lenses and grounding their eco-safety in both empirical studies and regulatory approvals, researchers and industries can optimize their applications to promote innovation, functional performance, and sustainability across multiple domains.

## 3 Bio-Mordants

Biomordants play a pivotal role in sustainable textile dyeing by promoting eco-friendly alternatives to conventional metal-based mordants. These organic substances, obtained from renewable biological sources, not only enhance dye uptake and fixation but also add functional benefits such as antimicrobial and UV-protective properties to textiles. Unlike conventional mordants—such as alum, copper sulfate, or chromium salts—that often pose toxicity and environmental concerns, biomordants are biodegradable, less hazardous to human health, and aligned with green chemistry principles.<sup>42,43</sup>

Biomordants can be broadly classified into two main categories based on their origin: vegetable-based and nonvegetable-based mordants. The former includes tannin-rich plants (e.g., Acacia, myrobalan, oak bark), fruits and seeds (such as amla, tamarind, guava), and herbaceous leaves (like aloe vera, peppermint, neem). These are rich in phenolic compounds and hydrolyzable tannins, which act as natural chelating agents that form complexes with dye molecules, thereby improving dye penetration and fastness properties. Their interaction with fiber substrates occurs through hydrogen bonding and van der Waals forces, often facilitated by mild acidic or enzymatic conditions.<sup>42,44</sup>

Nonvegetable-based biomordants comprise a diverse group, including chitosan (from crustacean shells), citric acid, eggshells, mushroom extracts, urine, and even enzymes like laccases and proteases. These components offer unique mechanisms for mordanting: for example, chitosan modifies surface charge properties of cellulose fibers, facilitating ionic interactions with anionic dyes, while enzymes can modify the fiber surface to improve dye adherence.<sup>42–43,45</sup> Some animal-derived substances like bile and gelatin were traditionally used for their nitrogen-rich nature and emulsifying properties, contributing to effective dye binding.

One of the key advantages of biomordants is their biocompatibility and environmental safety, which makes them especially valuable for dyeing products intended for direct skin contact, such as baby clothing and medical textiles. In comparison to synthetic mordants, biomordants offer a lower environmental footprint, reducing heavy metal discharge into effluents and avoiding the persistence of harmful residues in aquatic ecosystems.<sup>46</sup> Furthermore, many biomordants are derived from agricultural or

household waste (e.g., tea leaves, orange peels, coffee grounds), promoting waste valorization and supporting a circular economy.<sup>47</sup>

Their cost-effectiveness is also notable, as many of these substances are regionally abundant and do not require energy-intensive processing. Studies have shown that dyed fabrics treated with biomordants often exhibit enhanced fastness to washing and light, along with added functional properties like antimicrobial, antifungal, antioxidant, and even insect-repellent activity—attributes highly desirable in modern smart textile applications.<sup>48,49</sup>

The environmental benefits of biomordants go beyond just reducing chemical load—they also promote a paradigm shift toward green processing in the textile value chain. Biodegradable by nature, these mordants degrade into nontoxic compounds and are safe for disposal through natural cycles. Their renewable origin ensures resource conservation, while their compatibility with low-energy dyeing processes further contributes to reducing the carbon footprint of textile manufacturing. In essence, the strategic use of biomordants in natural dyeing systems represents a synergistic intersection of tradition and innovation. By harnessing nature-derived materials for mordanting, the industry can simultaneously achieve aesthetic quality, functional performance, and ecological responsibility. The sources and chemical structures of some commonly used biomordants are presented in [Table 1](#).

## 4 Mordanting Methods

Natural dyes often exhibit limited substantivity for textile fibers, particularly cellulose-based fabrics like cotton and linen. This limitation can result in poor color fastness, uneven dye uptake, and a narrow range of attainable shades. Mordanting addresses these challenges by serving as a chemical bridge between dye molecules and textile substrates, enhancing both dye fixation and durability.<sup>44,45</sup> The use of mordants significantly influences color outcomes and fastness properties, often expanding the functional scope and aesthetic versatility of natural dyes.<sup>46</sup> Depending on the sequence of application relative to dyeing, mordanting techniques are categorized into premordanting, simultaneous (meta-) mordanting, and postmordanting. Each method offers distinct process mechanisms, advantages, and limitations, which are discussed below. A simplified diagram of dye extraction and mordanting routes is provided in [Fig. 3](#).

The schematic diagram presented in [Fig. 3](#) illustrates the extraction, dyeing, and characterization workflow of prodigiosin pigment derived from the nonpathogenic bacterium *Serratia plymuthica*. This bio-based pigment, in its crude gel form, was applied to various multifiber textile substrates using a deep eutectic solvent (DES) composed of choline chloride and lactic acid (ChCl/LA, 1:2) as the dyeing medium. The diagram captures the key stages: microbial pigment production, extraction into a gel matrix, dyeing of fabrics under controlled conditions, and subsequent evaluation of color fastness and antibacterial efficacy. Notably, the addition of a biomordant and natural reducing agent significantly improved wash fastness, while the gel-based DES medium contributed to superior light fastness. The dyed nylon fabrics displayed remarkable antibacterial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa*, suggesting

the potential of prodigiosin in producing hygienic textiles. The diagram, therefore, not only reflects a closed-loop and green dyeing methodology but also highlights the synergy between microbial dyes, DES media, and biomordants in enhancing both aesthetic and functional textile properties—responding to growing global demands for sustainable alternatives to synthetic dyeing systems<sup>69</sup>

### 4.1 Premordanting

Premordanting is the most traditional and widely used approach in natural dyeing. It involves treating textile materials with a mordant solution prior to the dyeing process. During this phase, mordants interact chemically with the fiber's reactive groups—such as hydroxyl (–OH) in cellulose or amine (–NH<sub>2</sub>) in protein fibers—thereby enhancing dye affinity in subsequent steps.

Literature suggests that premordanting often results in higher dye exhaustion, more uniform shade development, and superior fastness properties due to the stable coordination complexes formed between the fiber and the mordant prior to dye contact.<sup>47,48</sup> For example, studies using alum and iron as premordants for turmeric and madder dyes demonstrated significant improvements in wash and light fastness values, compared to simultaneous or postapplication methods.<sup>70</sup> Additionally, this method enables batch mordanting, which is useful in industrial contexts for ensuring process standardization. However, the technique requires an additional processing step and consumes more water and energy, which may be a limitation in resource-sensitive environments. The effectiveness also varies with fabric type and the chemical structure of the mordant used.

### 4.2 Simultaneous (Meta-)Mordanting

Simultaneous mordanting, also known as meta-mordanting, entails the concurrent addition of mordant and dye into a single bath. This approach reduces the number of processing steps and simplifies workflow, making it suitable for small-scale or craft-based dyeing.

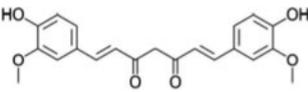
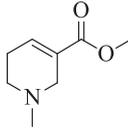
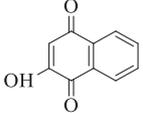
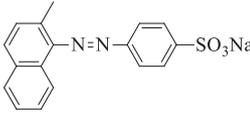
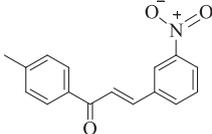
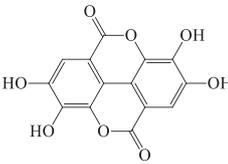
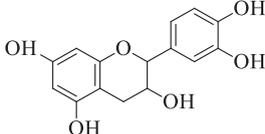
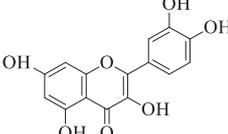
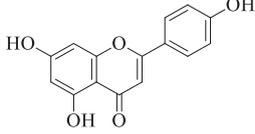
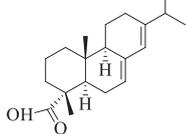
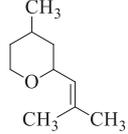
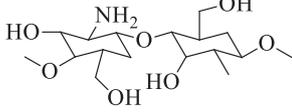
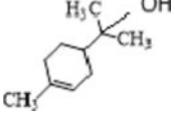
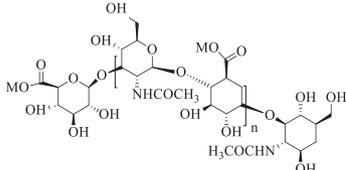
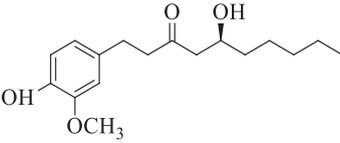
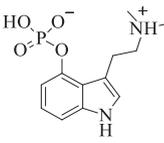
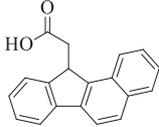
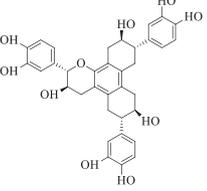
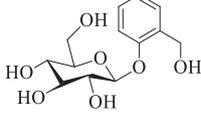
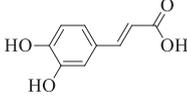
Despite its operational simplicity, simultaneous mordanting can lead to unpredictable shade variations and lower mordant uptake due to competition between dye and fiber for mordant binding sites.<sup>25,49</sup> Moreover, premature interaction between dye and mordant in the bath can lead to precipitate formation, reducing the effective dye concentration.<sup>71</sup> The dye–mordant–fiber tri-complex forms in situ, but may be less stable than complexes formed in pre- or post-treatment scenarios. Nevertheless, some dye–mordant pairs—especially those involving iron mordants and tannin-based dyes—perform well under this technique and can produce darker, more intense shades.<sup>42</sup> It is thus context-dependent and often selected when shorter dyeing cycles are prioritized over precision or reproducibility.

### 4.3 Postmordanting

In postmordanting, the mordant is applied after the dyeing process is complete. This method is especially useful when aiming to adjust shades or improve fastness after observing the initial dye outcome.

Postmordanting offers greater control over final shade development, particularly when using metal salts that can form different

**Table 1** Source and Structure of some common biomordants.

Chemical Structure	Source & Ref.	Chemical Structure	Source & Ref.
	Turmeric <sup>50</sup>		Areca nut <sup>60</sup>
	Henna powder <sup>51</sup>		Orange <sup>61</sup>
	Aloe Vera <sup>52</sup>		Pomegranate peel <sup>62</sup>
	Tamarind Seed Coat <sup>53</sup>		Onion peel <sup>63</sup>
	Prosopis Julipera <sup>54</sup>		Gum rosin <sup>64</sup>
	Rose <sup>55</sup>		Chitosan <sup>65</sup>
	Elaichi <sup>56</sup>		Egg shell <sup>66</sup>
	Ginger <sup>57</sup>		Mushrooms <sup>67</sup>
	Yeast <sup>58</sup>		Oak <sup>68</sup>
	Salicin (willow bark) <sup>59</sup>		Caffeic acid <sup>68</sup>

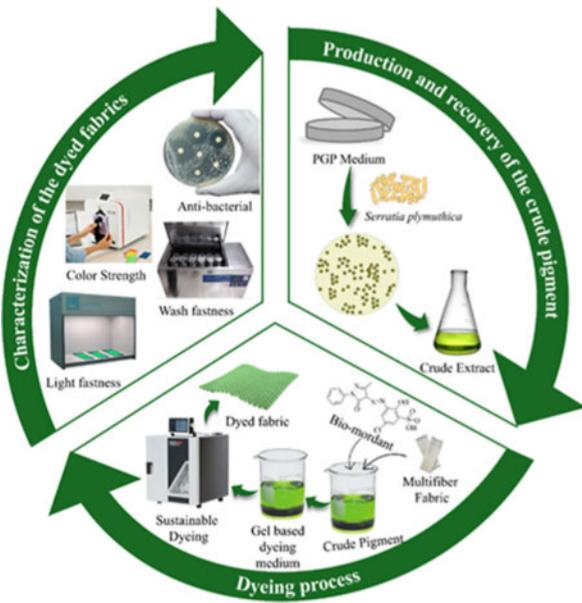


Fig. 3 A typical example of dye extraction and dyeing method.

colored complexes with the same dye molecule. This approach has shown notable results in producing richer shades with enhanced fastness, especially for protein-based fibers like wool and silk.<sup>25,49</sup> A study on the application of ferrous sulfate postmordant on dyed cotton revealed improved resistance to photo-fading and microbial degradation.<sup>72</sup> However, the interaction between the mordant and dye-fiber complex in postmordanting is highly variable, and its efficiency depends on fabric porosity, dye class, and mordant solubility. Moreover, longer processing times and higher water use may be needed to ensure uniform application. A schematic diagram of dyeing and mordanting methods is presented in Fig. 4.

#### 4.4 Comparative Analysis of Mordanting Techniques

The comparative evaluation presented in Table 2 synthesizes key practical and performance-oriented considerations across all three mordanting methods. It provides a decision-making framework for dyers, researchers, and manufacturers.

##### 4.4.1 Process Complexity

Pre and postmordanting involve separate steps for mordant and dye application, hence they are rated as “moderate” in complexity. Simultaneous mordanting combines both in a single step, simplifying workflow, which justifies its “simple” rating.<sup>72</sup>

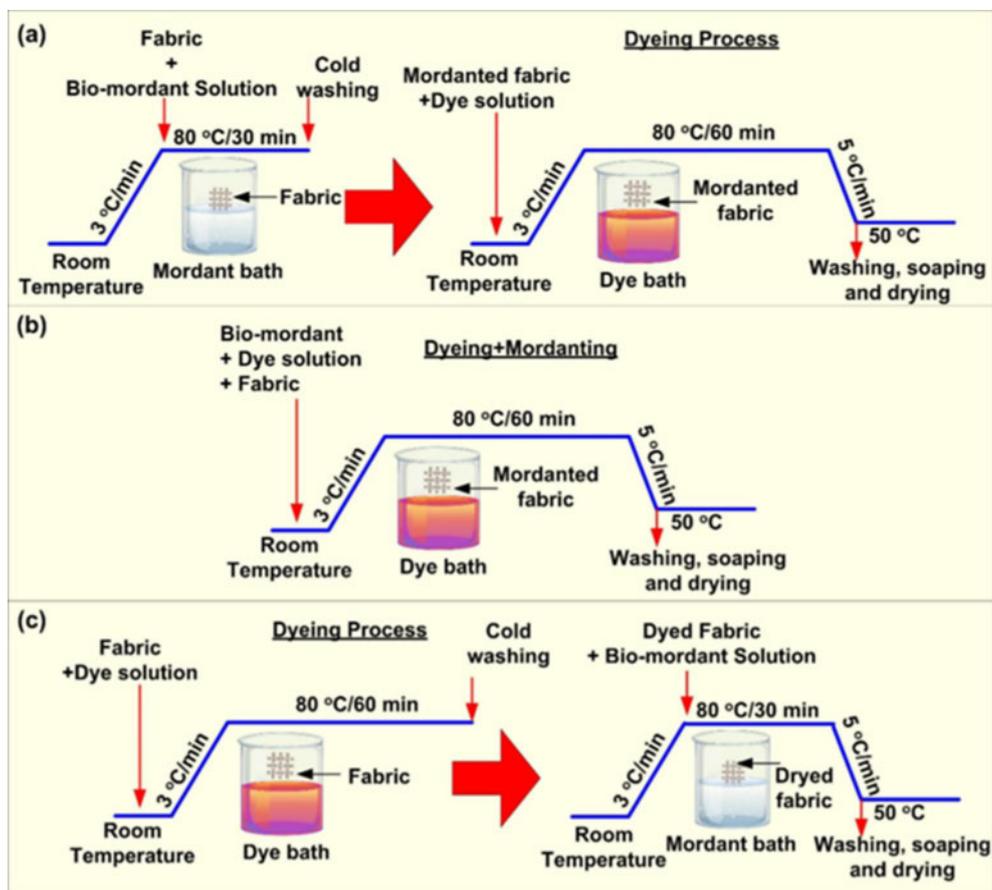


Fig. 4 Schematic diagram of dyeing and mordanting procedure (a) premordanting, (b) meta-mordanting, and (c) postmordanting.<sup>49</sup>

**Table 2** A comparative evaluation of the three mordanting techniques.

Technique	Process complexity	Resource efficiency	Shade consistency	Fastness properties
Premordanting	Moderate	Efficient	High	Excellent
Simultaneous Mordanting	Simple	Less Efficient	Variable	Good
Postmordanting	Moderate	Moderate	High	Excellent

#### 4.4.2 Resource Efficiency

Premordanting enables better mordant fixation and dye uptake, thus utilizing materials more efficiently. Simultaneous mordanting may lead to precipitates or incomplete bonding, making it “less efficient.” Postmordanting is intermediate, as it can recover inefficient dyeing but adds steps.<sup>73</sup>

#### 4.4.3 Shade Consistency

Pre- and postmordanting yield more consistent shades due to better control of mordant–fiber or mordant–dye interactions. In contrast, simultaneous mordanting can produce variable outcomes due to dynamic in-bath reactions, hence its “variable” rating.<sup>71</sup>

#### 4.4.4 Fastness Properties

Pre- and postmordanting typically achieve excellent fastness due to stronger dye–fiber–mordant complexation. Simultaneous methods, though quicker, may result in weaker bonding and thus “good” fastness.<sup>24,47–48</sup>

**Table 2** thus provides a holistic view, integrating both process efficiency and dye performance metrics. Its inclusion is intended to guide selection based on application needs, available infrastructure, and quality goals. A comparative evaluation of the three mordanting techniques highlights their relative strengths and weaknesses (**Table 2**).

The choice of the mordanting method depends on the desired color outcome, available resources, and the specific requirements of the dyeing process.

## 5 Fixing Mechanisms of Natural Dyes and Biomordants and Some Related Issues

The effective fixation of natural dyes on textile fibers is a critical determinant of both color depth and durability. The performance of natural dyes is governed by the nature of the fiber, type of mordant, and the bonding interactions involved. Biomordants, in particular, play a pivotal role in offering sustainable dyeing alternatives with enhanced performance and reduced environmental toxicity.

### 5.1 Chemical Bonding in Dye Fixation

Mordants act as bridging agents between dye molecules and textile substrates by forming chemical bonds, thereby improving dye substantivity, shade consistency, and fastness properties.<sup>70</sup> The nature and extent of bonding depend on the functional groups present on different fibers and dyes.

Cellulosic fibers (e.g., cotton, hemp, flax) are primarily composed of cellulose, which contains multiple hydroxyl (–OH) groups. These polar groups are capable of forming hydrogen bonds with dye molecules but exhibit limited ionic bonding due to the absence of amino or carboxyl groups. In contrast, protein-based fibers like silk and wool possess diverse reactive groups—amino (–NH<sub>2</sub>), carboxyl (–COOH), hydroxyl (–OH), and amide (–CONH<sub>2</sub>)—which enable multiple bonding mechanisms, including hydrogen bonding, ionic interactions, and covalent linkages.<sup>43,71</sup>

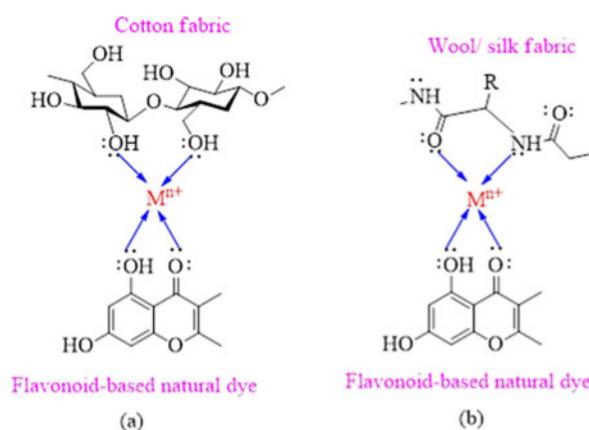
Hydrogen bonding occurs between –OH groups in cellulose or –NH<sub>2</sub>/–COOH in protein fibers and polar moieties in dyes. Ionic interactions are especially effective in protein fibers where oppositely charged groups on the dye and fiber enhance electrostatic attraction. Additionally, coordination complex formation is a key mechanism for metallic mordants, where transition metal ions coordinate with lone pair electrons from both the fiber and dye molecules to form stable, chelated complexes.<sup>42,71</sup>

These mechanisms are visually summarized in **Fig. 5**, illustrating how both cotton and wool/silk substrates interact with metallic mordants during dye fixation.

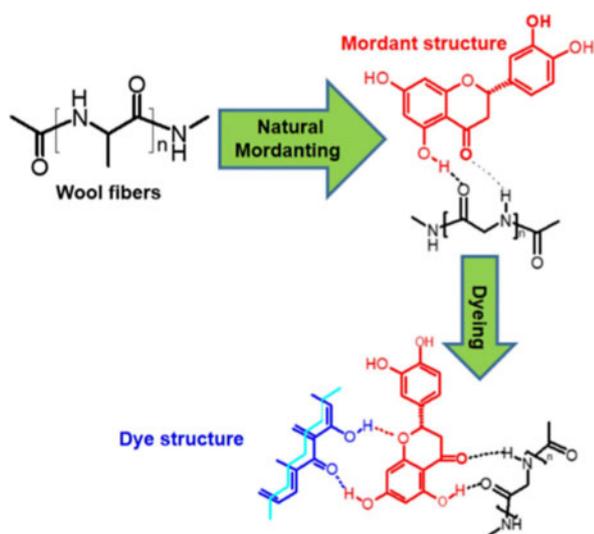
### 5.2 Role of Biomordants in Enhancing Dye–Substrate Interactions

Biomordants, derived from plant-based sources such as tannins, polyphenols, flavonoids, and organic acids, have shown growing potential as sustainable mordanting agents. Their polyfunctional chemical nature facilitates strong interactions with both fiber surfaces and dye molecules, forming hydrogen bonds, covalent linkages, and chelation complexes. These natural compounds not only enhance dye uptake but also improve color stability and reduce environmental impact.

In protein fibers, such as wool and silk, the presence of multiple functional groups like amino (–NH<sub>2</sub>), carboxyl (–COOH), and hydroxyl (–OH) enables robust bonding with biomordants. For example, tannins can form stable complexes through hydrogen bonding or covalent attachment, enhancing dye fixation and resulting in richer, deeper shades.<sup>72</sup> The interaction model depicted in **Fig. 6** illustrates these synergistic effects.

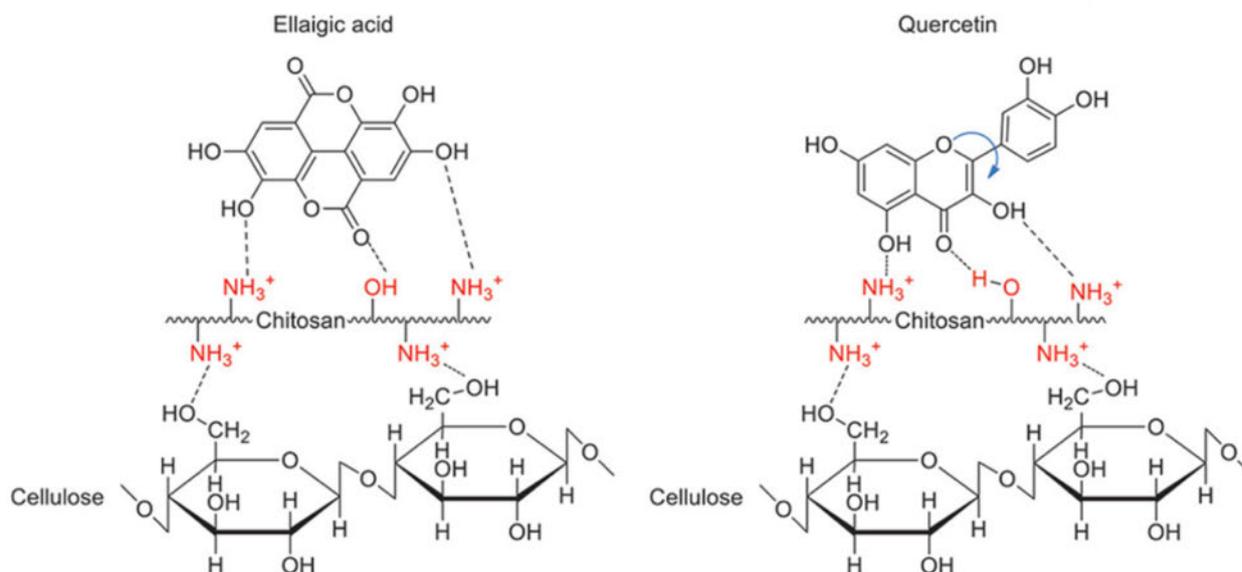


**Fig. 5** Bonding interactions between metallic mordants, natural dye, and fibers: (a) Mordanting cotton fabric and (b) Mordanting wool/silk.



**Fig. 6** Bonding interactions in the natural dyeing process: Wool, biomordant, and dye synergy.<sup>72</sup>

For cellulosic fibers, such as cotton, although reactivity is relatively lower due to limited functional sites, the application of biomordants like chitosan (a cationic biopolymer) or pomegranate extract can significantly improve dye adherence. These mordants interact via hydrogen bonding and chelation, promoting better dye fixation and color retention. **Fig. 7** shows how chitosan interacts with dyes from pomegranate rind and onion peel to improve adhesion to cotton.<sup>68</sup> Additionally, recent studies show that flavonoid-rich extracts like those from tea leaves, sumac, or arjuna bark further improve light fastness and color yield in cotton dyeing.<sup>73</sup>



**Fig. 7** Plausible mode of chelation in between the chitosan–cotton–colorant: (a) pomegranate rind extract and (b) onion peel extract.<sup>74</sup>

### 5.3 Impacts of Unbound Metallic Mordants on the Environment and Health

Although metallic mordants such as alum, copper sulfate, and iron salts are traditionally favored for their high fixation efficiency and shade diversity, their unbound residues pose serious ecological and health hazards. During dyeing, a portion of these mordants fails to bind with the fiber or dye and is released into wastewater. These residual metal ions contribute to aquatic toxicity, bioaccumulation, and long-term ecological disruption, with some like chromium VI known for carcinogenic effect.<sup>71,75</sup>

The use of biomordants addresses these concerns effectively. Plant-derived mordants are biodegradable, nontoxic, and generally safer for human health and the environment. For example, banana pseudo-stem sap, orange peel extract, and pomegranate rind not only reduce pollutant load in effluents but also exhibit comparable or even superior performance in dye fixation and fastness compared to metallic salts.<sup>76</sup> This makes biomordants an indispensable solution for sustainable textile processing.

### 5.4 Influence of Mordants on Color and Fastness Properties

The nature of mordant—whether metallic or bio-based—plays a critical role in determining the chromatic attributes and performance of dyed textiles. Metallic mordants are known for significantly altering the hue and deepening the tone due to complexation with dye molecules. However, biomordants often enhance brightness and color vibrancy while maintaining eco-friendliness.

**Table 3** presents extensive empirical data on the effects of various biomordants on dye uptake ( $K/S$  values), washing and rubbing fastness, and color depth across multiple fabric types.

**Table 3** Dyeing characteristics of natural dyes using biomordants.

Fabric	Natural Dye	Biomordant	Dyeing performance						Ref.	
			K/S value		Color fastness to wash		Color fastness to Rubbing			
			Without mordant	With mordant	Without mordant	With mordant	Without mordant	With mordant		
Cotton	Madder	Alum	-	-	2-3	3-4	-	-	75	
Silk	<i>Cuminum Cyminum</i> L	Tannic acid	-	-	3	4	-	-	77	
Cotton	Marigold flowers	Banana (Musa Sp.)	1.19	4.05	3	4-5	4-5	4-5	78	
Silk		Pseudo Stem Sap	0.69	1.54	1	1	4	4		
Cotton	<i>Hibiscus sabdariffa</i> L	Tannic acid	-	-	1-2	4-5	3-4	3-4	79	
		Pine cone				3-4		4		
		Lemon	-	-		3-4		4		
		Alginate	-	-		4		4		
Wool	<i>Carica papaya</i> leaf	Amla	2.467	3.689	4	4	3	4	80	
Silk		Harda	0.638	1.629		3-4		3		
Soya fabric		Orange peel	0.93	0.929		2-3		4		
Milk fabric		Pomegranate peel	0.597	1.996		2-3		3		
Wool fabric	<i>Quercus robur</i> L. (fruit cups) with <i>Salix alba</i> L.	Deltoides Bartram ex marsh (wood ash)	31.1	27.0	4	4	4-5	4-5	81	
Silk			18.1	26.2	4-5	5	5	5		
Cotton fabric			28.1	31.2	4	4	5	5		
Pashmina fabric			26.9	26.2	4-5	4	4-5	5		
Cotton Knit Fabric	Marigold	Arjuna	-	-	3	3	-	-	82	
		Eucalyptus bark				3-4				
		Khair				3-4				
Wool Fabric	<i>Berberis vulgaris</i> Wood	Rumex Hymenosepolus Root	30.08	57.21	3	4	3-4	4	83	
Wool Fabric	fruits of <i>Opuntia ficus-indica</i>	Chlorophyll- <i>a</i>	19.10	23.55	5	5	4	4-5	76	
Wool	Madder	Wellow Myrobalan (YM) and black Myrobalan	-	-	2	4-5	4	4-5	84	
Knitted Cotton Fabrics	Turmeric Powder	Colocasia Bulk	4	4.1	3-4	3-4	3	3-4	85	
		Lemon		7		4		4		
hemp fabric	<i>Buddleja officinalis</i>	<i>C. speciosa</i>	3.65	2.76	1	1	5	5	86	
		Gum rosin		3.98		1		5		
		Plant ash		3.81		1		5		
Silk fabric	Sappan wood	Waste oyster shell	7	16.1	2	3-4	-	-	49	
Leather	Walnut	Oxalic acid	-	-	3-4	5	3-4	5	87	
	Eucalyptus				4	5	3			
	Tea				3-4	4-5	3			
	Turmeric			3	4-5	3				
	Walnut	Acetic acid			3-4	4-5	3-4	4-5		
	Eucalyptus				4	4-5	3	4		
	Tea				3-4	4	3	4		
	Turmeric				3	3-4	3	5		
	Walnut		Citric acid			3-4	4	3-4		4
	Eucalyptus					4	4-5	3		4
Tea					3-4	4	3	4-5		
Turmeric				3	3-4	3	4-5			

(Continued)

**Table 3** (Continued)

Fabric	Natural Dye	Biomordant	Dyeing performance						Ref.
			K/S value		Color fastness to wash		Color fastness to Rubbing		
			Without mordant	With mordant	Without mordant	With mordant	Without mordant	With mordant	
Silk Fabric	Mango Leaves	Alovera	11.74	16.13	4	5	4–5	5	88
		Lemon		16.03		5			
		Myrobalan		10.84		4–5			
		Mango bark		12.14		4–5			

A few key patterns emerge from the table that warrant further discussion.

#### 5.4.1 K/S Values

The K/S (Kubelka–Munk) values indicate dye absorption efficiency. Biomordants like banana pseudo-stem sap, aloe vera, and wood ash show a marked increase in K/S values, especially in protein-based fabrics, indicating enhanced dye uptake. For instance, wool treated with *Rumex hymenosepolus* root shows K/S improvement from 30.08 to 57.21, almost doubling the dye absorption capacity.<sup>89</sup>

#### 5.4.2 Fastness to Washing and Rubbing

Color fastness to washing and rubbing generally improves with biomordant application. This can be attributed to the multiple bonding interactions facilitated by polyphenolic groups in biomordants. For example, mango leaves and myrobalan extracts provide excellent fastness ratings (4–5) on silk and cotton.<sup>88</sup> This enhancement is particularly notable in pashmina and wool, which show fastness levels of 4–5 even without synthetic fixatives.

#### 5.4.3 Comparison Across Fibers

Protein fibers like wool and silk consistently exhibit higher K/S values and better fastness ratings compared to cellulosic ones. This is due to the superior reactivity of protein fibers, which contain more diverse functional groups. However, when biomordants such as chitosan or citrus peel extract are applied to cotton, fastness properties approach those of protein fibers, showcasing the potential of biomordants to equalize dye performance across fiber types.<sup>90</sup>

#### 5.4.4 Functional Efficacy

In some cases, combinations of biomordants and dye precursors (e.g., madder with yellow and black myrobalan) yield not only improved fastness but also better shade consistency. These synergistic effects are likely due to chelation and multiple hydrogen bonds, reinforcing the dye–fiber–mordant complex.

These observations collectively underscore the promising performance of biomordants as both functional and ecological alternatives to their synthetic counterparts.

## 6 Impact of Biomordant Factors on Color Fastness

Biomordants, derived from plant-based compounds such as tannins, terpenoids, essential oils, and alkaloids, offer an eco-friendly alternative to metallic mordants in natural dyeing processes. They provide excellent color fixation while minimizing environmental hazards.<sup>42</sup> This section explores the impact of biomordants on color fastness properties, considering factors like concentration, pH, temperature, and mordanting techniques.

### 6.1 Effect of Biomordant Concentration on Color Fastness

The concentration of biomordants plays a crucial role in determining color yield and fastness. Higher biomordant concentrations enhance dye–fiber bonding by providing additional active sites for attachment, leading to improved color strength (K/S values) and fastness properties.<sup>74,91</sup> However, over-mordanting may result in uneven coloration or undesirable chemical reactions.<sup>76</sup> For example, dyed wool fabrics exhibited significant improvements in color values with increased bio-mordant concentrations.<sup>74</sup> Identifying the optimal concentration is essential to balance environmental sustainability with dyeing performance.<sup>90,92</sup>

### 6.2 Influence of pH and Temperature

The pH and temperature of the mordanting solution significantly influence dye uptake and color fastness. Adjusting the pH of the dye bath using agents like acetic acid or sodium carbonate can optimize fiber interaction. Studies indicate that pH values between 4 and 9 enhance color depth, while elevated temperatures (above 40 °C) facilitate fiber swelling and dye molecule diffusion, thereby improving color absorption.<sup>83,93</sup> However, excessive temperature increases may degrade dye molecules, leading to diminished color depth and fastness. Therefore, maintaining moderate conditions is vital for achieving consistent results.

### 6.3 Role of Additives in Dye–Fiber Interaction

Additives can amplify the effects of biomordants by improving dye–fiber interactions and enhancing color characteristics. For

instance, the addition of potash alum with biomordants increased the K/S values of jute fabric.<sup>94</sup> Similarly, Chairat et al. demonstrated the use of chitosan and glyoxal as crosslinking agents to improve color strength during cotton pretreatment with biomordants derived from *Mimosa pudica*.<sup>95</sup> These combinations not only enhance the dyeing process but also contribute to superior fastness properties.

## 6.4 Comparison of Premordanting vs. Postmordanting

### 6.4.1 Premordanting Technique

Premordanting involves treating fibers with biomordants before dyeing. This technique facilitates the formation of strong hydrogen or covalent bonds between the mordant and fiber functional groups, resulting in improved fastness and vivid shades. For example, combinations of metal salts (e.g., ferrous sulfate, stannous chloride) and bio-extracts (e.g., gallnut, pomegranate) produced textiles with enhanced colorimetric properties.<sup>47,96</sup> Wool samples premordanted with *Adhatoda vasica* leaf extract yielded attractive shades with acceptable fastness ratings.<sup>96</sup> Similarly, cotton treated with extracts of *Terminalia arjuna* bark or *Azadirachta indica* bark demonstrated superior color strength and fastness.<sup>97,98</sup> Additionally, *Peganum harmala* seeds and walnut bark-based juglone have been successfully employed in premordanting wool for vibrant hues and high fastness ratings.<sup>99,100</sup>

### 6.4.2 Postmordanting Technique

Postmordanting, where biomordants are applied after dyeing, enhances color depth, strength, and durability. For instance, treating silk and cotton with biomordants like turmeric and pomegranate extracts after dyeing with *Melia azedarach* bark improved fastness and yielded darker, richer shades.<sup>101</sup> Similarly, postmordanting wool with *Haematoxylum campechianum* wood extract or *Xanthium strumarium* leaf extract resulted in high K/S values and attractive hues under mild conditions.<sup>102,103</sup> This approach also allows for greater flexibility in achieving varied shades without compromising fastness.

The use of biomordants in natural dyeing offers promising avenues for sustainable textile production. Factors like biomordant concentration, pH, temperature, and mordanting technique significantly influence color yield and fastness. While premordanting ensures durable bonding and vibrant shades, postmordanting provides flexibility in achieving diverse color outcomes. Further exploration of biomordant combinations, additives, and application methods could pave the way for innovative and environmentally friendly dyeing practices.

## 7 Sustainable Resource Utilization for Biomordants

The increasing adoption of natural mordants as alternatives to hazardous metallic mordants marks a significant step toward eco-friendly and sustainable textile dyeing practices. Biomordants, derived from renewable resources such as plant roots, leaves, bark, agricultural waste, and certain animal-derived substances, are biodegradable, nontoxic, and contribute to vibrant and smooth

shades in textiles.<sup>104</sup> Their growing application reflects an urgent need to mitigate the carcinogenic and environmentally detrimental effects associated with synthetic mordants such as chromium salts, copper sulfate, tin chloride, and iron sulfate, which often remain unbound in wastewater, posing long-term ecological and health risks.

### 7.1 Identification of Renewable Biomordant Sources

The exploration of renewable biomordant sources has identified a wide variety of plant and agricultural waste materials with natural binding properties. For example, biomordants derived from pomegranate peel (*P. granatum* L.), gallnut (*Quercus infectoria* L.), and catechu (*Acacia catechu*) have been effectively applied on wool, showcasing their capacity to function as sustainable and metal-free alternatives.<sup>42,105</sup> Other notable examples include the outer green shell of almond fruit, investigated by İsmal et al.,<sup>106</sup> which serves as a biomordant capable of enhancing color strength while eliminating the need for metallic mordants. Similarly, the roots of *Rubia cordifolia*, used as 10% of the fabric's weight, were reported by Vankar PS et al.<sup>107</sup> to improve the fastness properties of dyed cotton. These findings demonstrate the diverse potential of renewable resources to serve as eco-friendly mordants.

In addition to these, leaves of *Terminalia arjuna*, banana pseudo-stem sap, orange peel, and coconut husk ash are also being explored for their tannin, polyphenol, and mineral contents that facilitate mordanting reactions in cellulosic and protein-based fibers.<sup>42,108</sup> These underutilized agricultural residues present valuable alternatives to synthetic and mined mordants, while also contributing to the bioeconomy through waste valorization.

### 7.2 Processing Methods to Optimize Resource Efficiency

Optimizing the extraction and application processes of biomordants is critical to maximizing their efficacy and reducing resource waste. Methods such as aqueous extraction and the use of minimal chemical solvents have been explored to ensure eco-friendly production. Mahreni et al.<sup>109</sup> demonstrated the use of *Centella asiatica* leaf extract as a biomordant for cotton dyed with *Bixa orellana*, showcasing an efficient extraction technique that ensures minimal environmental impact. Similarly, tannin-rich plants like *Rhus coriaria*, *Eucalyptus*, *Terminalia chebula*, and *Quercus castaneifolia* have been effectively processed to enhance color strength (K/S), washing fastness, and tensile properties of dyed fabrics.<sup>110</sup>

Other techniques such as sonication, microwave-assisted extraction, and enzymatic treatments are gaining momentum to further reduce the energy and solvent requirements of mordant production while enhancing the yield and reactivity of the active components. These process optimizations also support circular economy goals by minimizing the generation of by-products and enabling closed-loop practices within dyeing facilities.<sup>111</sup>

### 7.3 Waste Reduction and Circular Economy Approaches

The integration of biomordants into a circular economy framework is essential for minimizing waste and promoting regenerative

material flows within the textile value chain. Agricultural by-products such as *Eriobotrya japonica* (Loquat) seeds have been successfully used as natural mordants, demonstrating improved color strength and functional properties due to their polyphenolic content and natural affinity for fiber surfaces.<sup>101</sup> Similarly, *Bakain* bark (*M. azedarach* L.) has shown significant efficacy in enhancing shade variety and fastness performance on both cellulosic and proteinaceous substrates.<sup>112</sup>

Beyond these, a broader spectrum of agricultural residues—such as sugarcane bagasse, mango leaves, neem leaves, turmeric rhizome peel, tamarind seed coat, bamboo leaves, tea waste, and spent coffee grounds—are being increasingly studied for their potential as natural mordants or functional auxiliaries in natural dyeing.<sup>113</sup> These materials, often discarded or underutilized, are rich in tannins, lignins, and flavonoids that can act as natural chelators, enabling robust fiber–dye interactions.

In addition to replacing synthetic chemicals like alum, copper sulfate, and ferrous sulfate—known for their aquatic toxicity and bioaccumulation—the valorization of such wastes helps reduce chemical load in effluents and supports compliance with global environmental standards such as Zero Discharge of Hazardous Chemicals (ZDHC).

A well-articulated circular economy model in this context involves three key loops: (i) the input loop, where biomordants are derived from renewable agricultural and food processing residues; (ii) the process loop, where efficient extraction, application, and reuse of mordants (e.g., via repeated batch dyeing) are optimized; and (iii) the output loop, where spent mordant or dye sludge is composted, anaerobically digested, or repurposed for soil enrichment or biochar production.<sup>10</sup> This modeling supports sustainable production and consumption (SDG 12) by transforming linear “take–make–dispose” systems into regenerative cycles.

Moreover, closed-loop applications involving composting of exhausted mordant biomass or reuse in lower-value applications (e.g., geotextiles or nonwoven insulation) further enhance material circularity and reduce landfill burden. For instance, the residual sludge from mordant baths using *myrobalan* and *madder* has been shown to retain enough bioactivity for secondary use in paper coating and bio-pigments.<sup>10</sup>

The use of biomordants thus represents a transformative approach in sustainable textile dyeing, aligning with principles of renewable resource utilization, industrial ecology, and environmental stewardship. Ongoing research focused on techno-economic modeling, life cycle analysis, and system-level integration will further strengthen the industrial scalability and environmental justification for adopting circular biomordant systems.

## 8 Multifunctional Applications of Natural Dye with Biomordant

The integration of natural dyes with biomordants represents a significant advancement in textile manufacturing, offering a wide range of multifunctional applications. This emerging approach not only enhances the aesthetic and functional properties of textiles but also aligns with the growing demand for sustainable and eco-friendly solutions in the textile industry.

Biomordanted textiles have garnered attention for their potential applications in areas such as ultraviolet (UV) protection, antimicrobial activity, insect repellency, antioxidation, deodorizing, and antifungal properties, positioning them as innovative and versatile materials for modern use.

### 8.1 Balancing Aesthetics and Functionality in Textile Finishing

In contemporary textile finishing processes, achieving a harmonious balance between the desired functional qualities and the uniformity of finishing materials is essential. This delicate balance is particularly challenging with synthetic chemicals, which often pose health and environmental risks. Natural dyes combined with biomordants provide a safer alternative, offering multifunctional benefits without compromising ecological integrity.<sup>49,108</sup>

Biomordants such as tannins naturally exhibit antimicrobial properties, making them valuable in combating microbial growth on textiles—especially on natural fibers that are prone to such issues.<sup>49</sup> Unlike conventional antimicrobial agents like polybiguanides and triclosan, which may pose toxicity concerns for both humans and the environment, biomordants provide a green and safe solution.<sup>109</sup>

#### 8.1.1 Ultraviolet Protection and Skin Safety

The protective role of natural dyes in shielding the human skin from harmful UV rays is another noteworthy functional attribute. Natural colorants containing flavonoids, curcumin, and anthraquinones, derived from sources such as *Rheum emodi*, *Gardenia jasminoides*, *Lonicera periclymenum*, *Eucalyptus globulus*, *Citrus sinensis*, and *Pterocarya fraxinifolia*, have demonstrated the ability to absorb UV rays. These natural compounds, when used with biomordants, create textiles that effectively prevent UV radiation damage while maintaining their aesthetic appeal.<sup>110,111</sup>

#### 8.1.2 Antioxidant Properties for Enhanced Durability and Safety

Polyphenolic compounds present in plant-based biomordants such as tannins and flavonoids exhibit potent antioxidant properties, offering protection against oxidative damage and extending the durability of textiles. Research has highlighted the antioxidant activities of natural dyes and biomordants derived from plants such as *A. indica*, *M. azedarach*, *Q. infectoria*, *Acacia nilotica*, and *P. harmala*. These properties not only enhance the longevity of dyed fabrics but also contribute to a healthier environment for users by reducing exposure to harmful free radicals.<sup>101,112–113</sup>

#### 8.1.3 Deodorizing Capabilities for Modern Lifestyles

The demand for textiles with deodorizing properties has increased alongside contemporary concerns for personal hygiene and freshness. Studies reveal that textiles dyed with natural dyes such as *Paeonia suffruticosa*, *Syzygium aromaticum*, *Commiphora myrrha*, *Pinus albicaulis*, and others can absorb odor-causing gases, keeping fabrics fresh and suitable for prolonged wear. These applications are particularly appealing in sectors such as activewear, medical textiles, and everyday apparel.<sup>10</sup>

### 8.1.4 Insect Repellency and Antifungal Applications

Insect-repellent and antifungal properties are additional benefits offered by certain biomordants and natural dyes. Textiles treated with bio-active compounds derived from plant-based sources can help reduce the risks associated with insect bites and fungal infections. This function is particularly valuable in tropical regions and for outdoor applications, where users are more exposed to such risks.<sup>10,113</sup>

### 8.1.5 Antibacterial Properties of Natural Dye Biomordant Dyeing

The integration of antibacterial properties into textiles has become a significant focus in the industry, driven by consumer demand for health-promoting fabrics. Textiles serve as a primary interface between the human body and external environments, often acting as carriers for harmful bacteria. To address this, biomordant dyeing offers a dual advantage: enhancing the dyeing process while simultaneously imparting antibacterial properties through the natural medicinal components of the dyes and mordants.<sup>10,114</sup>

### 8.1.6 Green Alternatives to Traditional Methods

Conventional fabric dyeing and antibacterial finishing often rely on resource-intensive and environmentally damaging methods involving significant water, energy, and chemical consumption. In contrast, biomordant dyeing integrates antibacterial functionality into the dyeing process, eliminating the need for separate treatments. This approach reduces resource use and supports the principles of sustainable manufacturing.<sup>115,116</sup>

### 8.1.7 Antibacterial Efficacy in Textile Applications

Numerous studies have confirmed that biomordants, when used alongside natural dyes, can significantly enhance the antibacterial properties of textiles. For example, Adeel et al.<sup>117</sup> reported that wool fabrics dyed with anthocyanins extracted from rose petals exhibited strong antibacterial activity when treated with natural biomordants. Similarly, Shahmoradi et al.<sup>118</sup> found that cotton fabrics mordanted with tannic acid, pinecones, and lemon peels displayed superior antibacterial performance compared to those treated with synthetic alternatives. Indrianingsih et al.<sup>119</sup> demonstrated that cotton fabrics dyed using pigments from mango peels and *Ixora javanica* leaf powder as mordants showed notable antibacterial efficacy. Additionally, the use of *P. granatum* rinds and banana pseudostem sap as biomordants was shown by Ansari and Iqbal et al.<sup>120</sup> to provide strong resistance against common bacterial strains such as *Staphylococcus aureus* and *Escherichia coli*, further validating the potential of these natural agents in antimicrobial textile applications.

### 8.1.8 Innovative Techniques and Long-Lasting Effects

Advancements in biomordant dyeing techniques have led to durable antibacterial effects. For instance, silk fabrics dyed with red prickly pear fruit (*Opuntia ficus-indica*) using both natural and synthetic mordants demonstrated antibacterial resistance even after multiple washes.<sup>117</sup> Similarly, wool fabrics treated with chitosan–cyanuric chloride hybrids showed resistance to pathogenic bacteria across 20 wash cycles.<sup>10</sup>

### 8.1.9 Future Prospects in Antibacterial Textile Development

The incorporation of natural dyes and biomordants into textile production not only aligns with ecological and health-conscious trends but also opens up new avenues for functional applications. The development of biomordant dyeing methods with superior colorfastness, broad-spectrum antibacterial activity, and durability will continue to shape the future of sustainable textile manufacturing.

## 8.2 The UV Protection Properties of Natural Dye Biomordant Dyeing

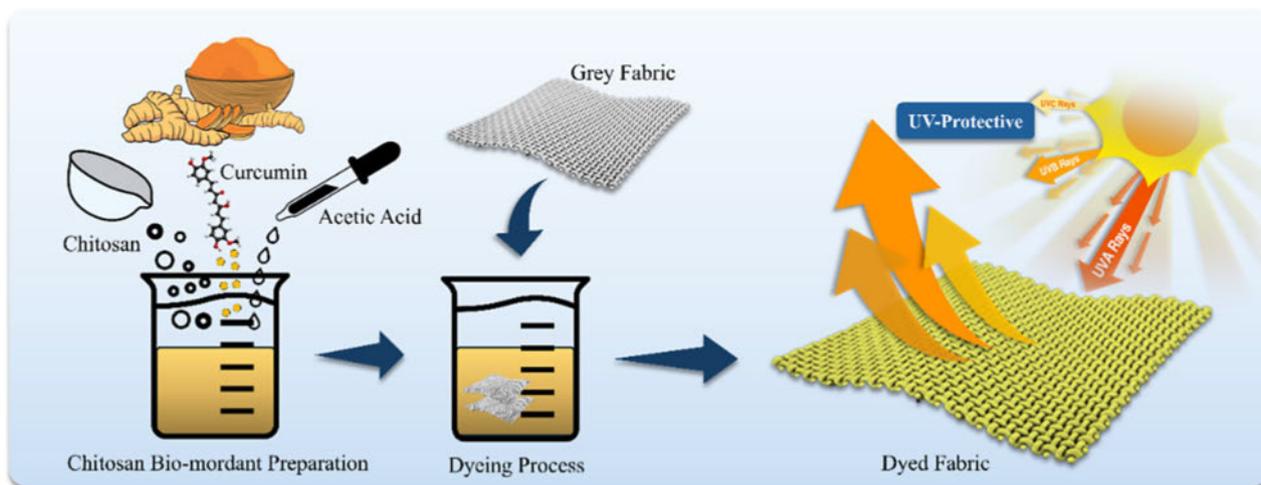
Natural dyes are increasingly valued for their environmental and health benefits, offering a sustainable alternative to synthetic dyes. One of the significant additional advantages of natural dyes lies in their potential to enhance UV protection properties of textiles. Overexposure to ultraviolet (UV) radiation can cause textiles to deteriorate rapidly, compromising their strength, abrasion resistance, and physical properties, and thereby reducing their lifespan. Moreover, UV exposure poses health risks, including skin disorders, immune system impairment, and vision problems, underscoring the need for UV-protective textiles. Consequently, researchers are exploring the UV-protection capabilities of natural dyes combined with biomordants, which not only enhance dye uptake but also improve UV shielding properties.

### 8.2.1 Studies on UV Protection with Natural Dyes and Biomordants

Recent research has increasingly demonstrated the promising role of natural dyes and biomordants in enhancing ultraviolet (UV) protection in textiles, making them not only aesthetically appealing but also functionally beneficial. For example, Singh<sup>114</sup> found that wool fabrics dyed with *Kigelia Africana* and biomordanted with *T. chebula* offered significant UV shielding, underscoring the multifunctionality of natural dye systems. Similarly, ultrasonic-assisted dyeing techniques using soy protein as a mordant improved the UV protection of cotton fabrics, as observed by Zhang et al.,<sup>115</sup> highlighting how innovative processing can synergize with biomordants to deliver superior performance.

Tannin-rich biomordants such as harda powder, pomegranate and orange peel, and amla were also reported to enhance the UV resistance of dyed wool fabrics.<sup>42</sup> Chao et al.<sup>116</sup> extended this to cotton and silk fabrics using *Phyllanthus emblica* as a mordant, demonstrating cross-fabric applicability. Grifoni et al.<sup>117</sup> emphasized that tannins from chestnut, when used with dyes like *Helichrysum italicum* and *Rubia peregrina*, improved UV resistance in cotton and jute, although alum proved more effective on flax, indicating the importance of matching dye, mordant, and fiber type.

Innovative use of sawdust extract from *Pterocarpus indicus Willd.*, applied via ultrasound-assisted dyeing and paired with natural mordants like gallnut, pomegranate peel, and gooseberry, led to enhanced UV protection and color performance in both cotton and silk.<sup>118</sup> Likewise, jute fabrics dyed with marigold and pomegranate and premordanted with harda showed high UV protection.<sup>119</sup> Myrobalan, a well-known tannin-based mordant,



**Fig. 8** Chitosan-based biomordant for curcumin dyeing: enhancing UV protection in textiles.

has proven effective in improving the UV-blocking capacity of silk and wool fabrics alongside natural dyes.<sup>120,121</sup>

Further, Grifoni et al.<sup>122</sup> confirmed that gallnut-based mordants could significantly elevate UV protection in plant-based fabrics like cotton, hemp, and linen, with some untreated fabrics reaching excellent UV protection levels when structurally optimized. Chitosan has also emerged as a powerful biomordant; Fang et al.<sup>123</sup> demonstrated that chitosan-pretreated cotton dyed with lotus seedpod extract achieved a UPF of 63.4, maintaining protection even after washing. A similar finding by Do et al.<sup>124</sup> with chitosan and *R. cordifolia* dyed silk reinforced chitosan's effectiveness. **Fig. 8** illustrates this enhancement with curcumin dyeing.

Tu et al.<sup>125</sup> further showed that the use of *Coptis chinensis* and citric acid could push UPF values of cotton fabrics to over 349, showcasing the transformative potential of biomordants in textile UV protection. Finally, Phromphen et al.<sup>126</sup> demonstrated that banana peel tannins, in combination with marigold extracts, significantly boosted UV resistance in cotton fabrics, reinforcing the value of agro-waste-derived mordants in protective textiles.

### 8.2.2 Challenges and Future Directions of UV Protection

Despite significant progress, creating UV-protective natural dyeing techniques that meet contemporary standards remains a challenge. Key areas for future development include.

- *Enhanced UV Resistance*

Developing biomordants that offer long-lasting UV protection even after multiple washes.

- *Sustainable Alternatives*

Exploring waste-derived biomordants and renewable natural dye sources to improve ecological sustainability.

- *Improved Color Fastness*

Ensuring that the UV protection properties are complemented by superior fastness to washing, light, and rubbing.

- *Fabric-Specific Solutions*

Customizing biomordant and dye combinations to suit different fabric types and construction methods.

The integration of advanced technologies such as ultrasound-assisted extraction, nanotechnology, and bio-functional finishes with natural dyeing processes holds promise for the textile industry. By addressing these challenges, researchers can pave the way for eco-friendly, UV-protective textiles that align with both environmental goals and consumer needs.

## 8.3 Antioxidant and Other Functional Properties of Natural Dye Biomordants

In recent years, consumer preferences have increasingly shifted toward high-quality, natural, safe, and protective textiles, underscoring the growing importance of “functionality” and “practicality” in the textile fabric industry. The integration of natural dye biomordant dyeing processes with the development of functional textiles—such as those offering antioxidant, insect-repellent, and flame-retardant properties—has garnered substantial interest from researchers and end-users alike. This synergy aligns with global trends favoring sustainable, eco-friendly practices in textile manufacturing.

### 8.3.1 Antioxidant Properties

The incorporation of biomordants has been pivotal in enhancing the antioxidant properties of textiles. For instance:

Kushwaha et al.<sup>127</sup> successfully used *A. nilotica* bark as a biomordant in combination with *Nyctanthes arbor-tristis* natural dye to achieve an impressive antioxidant activity of 99.37% against 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radicals on pineapple fabrics. Safapour et al.<sup>128</sup> demonstrated improved antioxidant properties by dyeing wool yarns with *Melissa officinalis* L. natural dye using 75% biomordants derived from *Q. infectoria* and Eucalyptus bark. Wang et al.<sup>129</sup> used microwave extraction to isolate melanin from goji berry residue, creating microcapsule dyes encapsulated with phospholipids and utilizing pomegranate peel as a biomordant. This innovative approach produced wool fabrics

with excellent antioxidant properties, adhering to energy-saving and emission-reduction principles.

Zhou et al.<sup>130</sup> extracted pigments from tannin-rich tallow leaves, combined with chlorophyll extract as a biomordant to dye wool fabrics. The resulting deep yellow wool demonstrated robust antioxidant activity, highlighting its potential for bioactive medical material applications. A notable study focused on dye extraction from the bark peel of *Araucaria columnaris* compared various mordanting techniques (premordanting, simultaneous mordanting, postmordanting using alum and myrobalan) with dyeing sans mordant. The DPPH assay confirmed positive antioxidant properties across all dyed samples, demonstrating the potential for cotton fabrics to possess efficient antioxidant properties.<sup>131</sup>

### 8.3.2 Insect-Repellent Properties

Natural dye biomordants also exhibit significant insect-repellent properties:

Barani et al.<sup>132</sup> treated wool fibers with *Hymenocrater platystegius* flower powder and dyed them with madder, *Reseda lutea*, indigo, and walnut shell dyes using various mordanting techniques. The treated fibers displayed a notable reduction in weight loss caused by *Anthrenus verbasci* larvae, demonstrating the flower powder's robust insect-repellent efficacy.

### 8.3.3 Flame-Retardant Properties

The use of biomordants for flame-retardant applications has been equally promising:

Bar et al.<sup>133</sup> investigated eco-friendly dyeing and flame-retardant finishing of silk fabrics using *Bauhinia vahlii* bark extract with citric acid as a bio-acid. Further treatment with banana peduncle extract (BPE) enhanced the functional properties, including flame retardancy. Kishor et al.<sup>89</sup> premordanted wool fabrics with amla dye (AR), baheda (BR), and harda (HR) mordants in an infrared dyeing machine, subsequently dyeing with straw powder extract. This process yielded wool fabrics with exceptional flame-retardant properties (LOI > 30) and water vapor permeability (>2500 g/m<sup>2</sup>/24 h).

### 8.3.4 Multifunctionality and Future Scope

Multifunctional textiles—combining antioxidant, insect-repellent, and flame-retardant properties—offer innovative solutions for healthier, more sustainable fabrics. For example:

Jabar et al.<sup>134</sup> explored eco-safe dyeing using *Vernonia amygdalina* with cashew bark (CB) and *Sorghum bicolor* leaf extracts as biomordants for cotton fabrics. The resulting textiles exhibited enhanced antioxidant properties after herbal postmordanting. The sequence of antioxidant efficiency was as follows: RCF < RCF-CB < RCF-CC-CB < RCF-IS-CB < RCF-VAL-CB < RCF-SBL-CB. Notably, antioxidant functionality was retained even after seven laundry cycles.

## 9 Biocompatibility and Toxicological Aspects

As the demand for safer and more sustainable textile processing intensifies, the biocompatibility and toxicological profile of natural

dyes and biomordants have become crucial considerations. This section explores how biomordants interact with different fiber substrates, evaluates their cytotoxic potential through scientific studies, and discusses their broader safety implications for end users. These insights help establish biomordants as not only environmentally sound but also health-conscious alternatives to conventional dyeing agents.

### 9.1 Biocompatibility of Biomordants with Different Substrates

Biomordants have emerged as eco-friendly alternatives to metallic mordants, which are often associated with environmental hazards and health risks. Derived from natural sources such as plants, fungi, algae, and minerals, biomordants not only provide vivid and stable colors but also exhibit remarkable biocompatibility with various substrates. Their application enhances dye adherence, resulting in improved colorfastness properties, while simultaneously imparting functional properties to the fabrics.<sup>135</sup>

Recent advancements in natural dyeing processes have enabled the development of innovative biomordants that improve the durability and aesthetics of textiles. For instance, the phytochemical constituents of Arjun (*Terminalia arjuna*), such as ellagic acid and baicalein, not only enhance the reddish-brown coloration of natural fabrics but also confer anti-inflammatory, antioxidant, antibacterial, and antiviral properties, making the dyed fabrics beneficial for therapeutic applications.<sup>135–137</sup>

Similarly, Manjakani (*Q. infectoria*), rich in tannins, gallic acid, and syringic acid, has shown promising results as a biomordant. Studies have demonstrated its effectiveness in enhancing the vibrancy of silk and wool fabrics when combined with natural dyes such as sumac and myrrh.<sup>138,139</sup>

Other biomordants like *Mucuna pruriens*, known for its alkaloids, flavonoids, and phenols, have been utilized to dye silk fabrics using mango peels as a dye source, yielding aesthetically pleasing and bioactive textiles.<sup>140,141</sup> *Myrica esculenta*, containing gallic acid and myricanol, has also been employed to dye cotton fabrics, imparting medicinal benefits alongside color stability.<sup>142</sup> The versatile therapeutic properties of *A. indica* (neem) make it a notable biomordant. With over 140 bioactive compounds, neem extracts have been effectively used to improve the colorfastness and antimicrobial properties of natural dyes.<sup>143,144</sup>

### 9.2 Evaluation of Cytotoxicity

The cytotoxicity evaluation of natural dyes and biomordants is critical to ensuring their safety for end users. Unlike synthetic dyes, which often pose significant health hazards, natural dyes and biomordants exhibit low toxicity and reduced allergenic potential, making them suitable for applications in textiles, cosmetics, and other industries.<sup>145</sup>

For instance, Yaglıoğlu et al.<sup>146</sup> demonstrated that the aqueous extract of *Alkanna orientalis* roots exhibited 0% cytotoxicity on cotton, viscose, and wool fabrics, indicating its safety for use in textiles. Similarly, the ethanolic and water extracts of *Genipa americana* L. dye were tested on MRC-5 human fibroblasts, showing 95.1% cell viability at a concentration of 100 µg/mL, underscoring its biocompatibility.<sup>147</sup> Another study by Ab Kadir et al.<sup>148</sup> investigated the cytotoxicity of dyes derived from

Sargassum sp. and *Caulerpa lentillifera* algae. Their findings confirmed the nontoxic nature of these materials, with extracts showing high cell viability, making them safe alternatives for dyeing silk fabrics.

Conversely, cytotoxicity assays using the brine shrimp lethality bioassay for *Curcuma longa* L. extracts revealed LC50 values of 207.182 ppm and 323.752 ppm for water and ethanol extracts, respectively, indicating their potential bioactivity at specific concentrations.<sup>149</sup> These findings highlight the need for precise control over dye concentrations during textile applications to ensure safety.

### 9.3 Safety Implications for End Users

The incorporation of natural dyes and biomordants in textiles offers significant safety advantages for end users. The absence of harmful chemicals reduces the risk of allergic reactions, skin irritations, and long-term health issues. Additionally, the bioactive properties of biomordants, such as antimicrobial and anti-inflammatory effects, further enhance the usability and functionality of textiles. For example, dyed fabrics using *Sargassum* sp. extracts demonstrated improved cell viability and bioactivity, providing added health benefits.<sup>148</sup>

Moreover, the environmental safety of natural dyes and biomordants ensures minimal ecological impact during production and disposal, addressing concerns related to pollution and sustainability. By replacing synthetic dyes with biocompatible alternatives, industries can cater to consumer demands for eco-friendly and health-conscious products while promoting sustainable practices.

## 10 Future Perspectives of Natural Dyes and Biomordants

Natural dyes and biomordants represent a promising pathway toward sustainable textile manufacturing due to their environmentally friendly properties, renewability, and reduced reliance on synthetic alternatives. As the industry increasingly embraces eco-conscious practices, the following advancements and opportunities emerge:

### 10.1 Advancements in Biomordant Chemistry

The field of biomordant chemistry has witnessed considerable progress in recent years, driven by the urgent need to replace toxic and nonbiodegradable metallic mordants like chromium and copper with safer, environmentally benign alternatives. Biomordants sourced from plant extracts, minerals, and organic residues have emerged as viable options due to their biodegradability, functional properties, and compatibility with natural dyes.<sup>150,151</sup> Ongoing future research in this domain is expected to refine the chemical structure and performance of biomordants to enhance their binding efficiency, stability, and colorfastness across a wide range of textile substrates. Advances in green chemistry are crucial for this transition, particularly in developing eco-friendly extraction and synthesis methods that reduce solvent use and lower the environmental footprint of mordant production.

In parallel, nanotechnology presents promising avenues to boost the uniformity and efficiency of mordant–dye–fiber interactions. The incorporation of nano-biomordants could significantly reduce the required mordant quantity while achieving improved fixation and color durability. Additionally, there is growing interest in utilizing locally available agro-waste and underutilized biomass to develop region-specific mordant solutions. This approach supports circular economy models by minimizing transportation costs and valorizing renewable resources that would otherwise be discarded.

### 10.2 Integration of Natural Dyes in High-Performance Textiles

Natural dyes, once limited to artisanal and cultural textiles, are increasingly being considered for high-performance applications due to their biocompatibility, antioxidant potential, and UV-protective properties. These dyes are now being explored for use in technical textiles such as UV-protective garments, antimicrobial hospital fabrics, and therapeutic textiles for wound healing or sensitive skin.<sup>152,153</sup> The integration of traditional dye sources into contemporary textile engineering reflects a promising fusion of heritage and innovation.

Advancements in dyeing methods—such as ultrasound-assisted dyeing, enzymatic treatments, and the use of biomordants—are being developed to overcome the challenges of uneven dyeing, low yield, and poor reproducibility that have historically hindered the commercial use of natural dyes. By improving dye penetration and uniformity, these techniques enable more consistent results that are suitable for industrial applications. Such efforts are paving the way for the broader adoption of natural dyes in mainstream textile production.

### 10.3 Opportunities for Industrial Scalability and Commercialization

For natural dyes and biomordants to transition from small-scale or niche applications to industrial adoption, several technical, economic, and regulatory barriers must be addressed. One of the foremost challenges is the adaptation of automated dyeing technologies that can accommodate the variability and composition of natural dye formulations. Automating these processes is essential to achieving the consistency and efficiency required for mass production.

The establishment and expansion of certification frameworks—such as the Global Organic Textile Standard (GOTS)—are equally important. These standards can incorporate clear criteria for the use of natural dyes and biomordants, helping to boost consumer confidence and facilitate global market access.<sup>26</sup> Cost-efficiency remains a critical factor; thus, optimizing extraction and mordanting processes, promoting the use of locally sourced biomass, and valorizing agricultural by-products can make natural dyeing more economically viable.

Collaboration among research institutions, industry stakeholders, and policymakers is vital for driving innovation and ensuring the scalability of natural dye technologies. Joint efforts can lead to the development of tailored dyeing systems, improved mordanting chemistries, and sustainable supply chains that serve both commercial and environmental interests.

### 10.3.1 Environmental and Social Impacts

The shift toward natural dyeing systems has broad environmental and social implications. Environmentally, dye plant cultivation can contribute to biodiversity conservation and promote agroforestry systems that regenerate degraded lands.<sup>154–159</sup> The reduced toxicity of natural dye effluents also eases the burden on water treatment infrastructure, resulting in less water pollution and lower ecological impact.<sup>42,160</sup>

On the social front, the promotion of natural dyeing can empower rural communities by creating income-generating opportunities and preserving traditional knowledge systems. Community-based dye production can revitalize artisanal practices while meeting modern sustainability standards. Furthermore, the low allergenic and toxicological profiles of natural dyes make them safer for both consumers and workers across the textile value chain, thus improving overall public health outcomes.<sup>152,153</sup>

### 10.3.2 The Road Ahead

To fully unlock the potential of natural dyes and biomordants, strategic support from government bodies, industry leaders, and consumers is essential. Policy interventions such as subsidies for eco-friendly dyeing operations, grants for R&D, and tax incentives for sustainable textile initiatives could accelerate the transition. Raising consumer awareness through educational campaigns about the environmental and health benefits of natural dyeing practices will help foster demand-driven innovation.

Finally, building strong networks among researchers, dyers, farmers, brands, and regulatory bodies will enable integrated, scalable solutions that balance performance, sustainability, and economic feasibility. Through these collective efforts, natural dyes and biomordants can become integral components of a truly sustainable and responsible textile industry.

## 11 Drawbacks and Challenges of Natural Dyes and Biomordants

While natural dyes and biomordants present eco-friendly alternatives to synthetic counterparts, several drawbacks and challenges hinder their broader adoption. These limitations are multifaceted and encompass issues related to availability, variability, cost, technological gaps, and sustainability. Below, these challenges are elaborated upon:

### 11.1 Limited Availability of Raw Materials

The production of natural dyes heavily depends on organic sources such as plants, minerals, and insects, many of which are region-specific and seasonal. Habitat destruction, climate change, and overexploitation often lead to shortages or variability in raw material availability. For instance, plants grown in different soil types or climates may yield dyes with inconsistent shades or properties. This scarcity limits scalability and makes it difficult to meet the growing demand for natural dyes, especially in industrial applications. Additionally, unsustainable harvesting practices can exacerbate resource depletion, posing a threat to biodiversity and long-term supply stability.<sup>161–163</sup>

### 11.2 Variability in Dyeing Outcomes

Natural dyes inherently exhibit significant variability in dyeing outcomes due to their organic origins. Factors such as soil composition, weather, harvesting conditions, and storage can influence the quality and chemical composition of natural dyes, resulting in inconsistency in shade, intensity, and colorfastness across batches. This variability poses a challenge for industries that require precise color matching and uniformity, such as textiles and cosmetics. The lack of standardization in natural dyeing processes further complicates their use in large-scale production, reducing their appeal to commercial manufacturers.<sup>164</sup>

### 11.3 High Cost and Resource-Intensive Processes

The extraction and application of natural dyes are more labor- and resource-intensive compared to synthetic dyes. The processes often involve lengthy preparation steps, such as dye extraction, mordanting, and prolonged dyeing cycles, which increase production time and costs. The yield of dye extracted from natural sources is often low, requiring larger quantities of raw materials, which further drives up costs. For example, the need for biomordants or additional treatments to enhance color intensity and fastness adds to the complexity and expense of natural dyeing. In competitive markets, these high production costs make it difficult for natural dyes to compete with their synthetic counterparts.<sup>165</sup>

### 11.4 Knowledge Gaps and Technological Limitations

Despite advancements, significant knowledge gaps and technological limitations persist in the natural dyeing sector. The absence of standardized extraction, characterization, and application methods makes it challenging to achieve consistency and efficiency. Limited research and development investments have hindered innovations in improving the color range, fastness, and usability of natural dyes. Furthermore, a lack of awareness and expertise among artisans and manufacturers on optimizing natural dyeing processes acts as a barrier to widespread adoption. Technological interventions are needed to simplify processes, reduce costs, and ensure reproducibility in dyeing outcomes.<sup>166</sup>

### 11.5 Additional Challenges

#### 11.5.1 Narrow Shade Range

Natural dyes often provide a limited color palette dominated by earthy and muted tones. The inability to achieve vibrant, bright colors restricts their application in industries like fashion and cosmetics, where a diverse range of hues is demanded.<sup>164</sup>

#### 11.5.2 Poor Colorfastness

Natural dyes are generally less resistant to fading from exposure to light, washing, and abrasion compared to synthetic dyes. This limitation is particularly problematic for textiles used in outdoor or high-traffic applications, where durability is essential. Improved biomordants and dyeing techniques are needed to address this issue.<sup>167</sup>

### 11.5.3 Health Risks

While natural dyes are perceived as safe, some may contain allergenic or toxic compounds. Improper handling during extraction and dyeing processes can pose health risks to workers, such as skin irritation or respiratory issues. End users may also experience adverse reactions if residues remain on dyed products.<sup>168,169</sup>

### 11.5.4 Environmental Concerns

Despite their eco-friendly image, the increased demand for natural dyes can lead to deforestation, habitat loss, and ecosystem disruption. For instance, overharvesting dye-yielding plants can degrade biodiversity, while large-scale cultivation may result in the conversion of natural habitats into agricultural land. These practices can have long-term environmental consequences, including exacerbating climate change.<sup>161–163</sup>

### 11.5.5 Certification and Quality Assurance Issues

Unlike synthetic dyes, which are chemically standardized, the variability in natural dyes makes them difficult to certify for quality, safety, and authenticity. This lack of certification standards undermines consumer trust and poses challenges for manufacturers aiming to produce consistent and reliable products.<sup>166</sup>

### 11.5.6 Industrial Incompatibility

Natural dyes often fail to meet the stringent requirements of industrial-scale operations, such as rapid dyeing processes, batch-to-batch consistency, and high throughput. Longer processing times and the need for higher dye concentrations also reduce efficiency, making them less viable for mass production.

## 12 Next-Generation Natural Dyes and Biomordants

The pursuit of sustainability in textile production has prompted significant research into next-generation natural dyes and biomordants. The textile industry, historically reliant on synthetic dyes and mordants, is increasingly turning toward more environmentally friendly alternatives. This evolution is driven by a growing demand for eco-conscious materials and processes, alongside concerns regarding the environmental and health impacts of synthetic dyes. Researchers are exploring a variety of innovative approaches that focus on harnessing the power of biotechnology, nanotechnology, and sustainable agriculture to develop dyes and mordants that are not only effective but also sustainable and safe for both people and the planet.

### 12.1 Bioengineered Dyes and Biomordants

Bioengineering is rapidly emerging as a promising strategy to develop novel, sustainable dyes and biomordants. One of the most exciting developments in this field involves the use of microorganisms to produce dyes. Microbial pigments, derived from bacteria, fungi, algae, and yeasts, offer a sustainable alternative to traditional plant-based and synthetic dyes. These microorganisms can produce a wide range of vibrant hues, from reds and blues to purples and yellows, in a controlled, reproducible manner. Additionally, they can be engineered to optimize pigment yield and color stability, making them a highly promising

option for industrial applications. For example, *Rhodobacter sphaeroides* has been used to produce purple pigments, while *Monascus* fungi generate a wide array of colorant compounds that can be adapted for various textile applications.

In addition to microbial pigments, bioengineered dyes from plants are also being developed. Advances in plant breeding techniques, such as genetic modification, are enabling the production of crops that yield pigments with enhanced color strength, stability, and ease of extraction. These crops are not only sustainable but also offer potential economic benefits by reducing the cost of dye production. Bioengineered dyes could reduce the need for harmful chemical treatments during the extraction process and could be cultivated with fewer resources and less environmental impact compared to traditional agricultural methods.

Furthermore, bioengineered biomordants are gaining attention as eco-friendly alternatives to the conventional mordants, which often rely on heavy metals like chromium. Chitosan, derived from chitin (a natural polymer found in the exoskeletons of crustaceans), has emerged as a promising biomordant due to its biodegradability, nontoxic nature, and effectiveness in enhancing dye uptake and color fastness. Additionally, tannins, polyphenolic compounds found in various plant species, are being investigated for their potential to serve as natural mordants. These biomordants offer an alternative to chemical mordants, improving the colorfastness of natural dyes without posing significant risks to human health or the environment.

### 12.2 Utilization of Nanotechnology for Improved Performance

Nanotechnology has the potential to revolutionize the use of natural dyes and biomordants by enhancing their performance and expanding their applications. By manipulating materials at the nanometer scale, researchers can improve the colorfastness, stability, and applicability of natural dyes. For instance, nanoencapsulation of natural dyes in nanocarriers such as nanoparticles, liposomes, or dendrimers can protect the dye molecules from environmental factors such as UV radiation, moisture, and air, significantly improving their lightfastness and washing fastness. This technique also allows for the controlled release of dye molecules onto textile fibers, enhancing uniformity and color intensity.

Nanotechnology can also be used to modify natural fibers and biomordants, improving their interaction with natural dyes. Nanomaterials such as silver, copper, and silica nanoparticles can be incorporated into textiles to enhance their color retention and durability. These nanoparticles can act as catalysts in the dyeing process, allowing for the use of lower concentrations of natural dyes and reducing the environmental footprint of dyeing processes. Additionally, the use of nanoparticles can lead to textiles with improved antimicrobial properties, further enhancing their value in sectors such as healthcare, sportswear, and outdoor apparel.

Furthermore, nanostructured biomordants are being explored to enhance their effectiveness. By engineering nanomaterials that can interact more effectively with natural dyes and textile fibers, researchers can improve color intensity, wash fastness, and overall durability. This combination of nanotechnology with natural dyes and biomordants offers exciting possibilities for

developing next-generation textiles that are both sustainable and high-performance.

### 12.3 Hybrid Systems Combining Natural and Synthetic Approaches

While natural dyes and biomordants are gaining traction, there are still challenges associated with their consistency, performance, and color range. To address these issues, hybrid systems that combine natural and synthetic approaches are being developed. These systems aim to leverage the best of both worlds, combining the sustainability and eco-friendliness of natural dyes with the colorfastness, uniformity, and versatility of synthetic dyes.

For example, researchers are exploring the use of natural dyes in combination with synthetic mordants that are less harmful than traditional chemical mordants. This hybrid approach can enhance the color retention and fastness properties of natural dyes while maintaining a reduced environmental impact. Alternatively, synthetic dyes can be used to supplement natural dyes, achieving the desired color shades without compromising sustainability.

Another promising hybrid approach is the combination of natural dyeing with synthetic polymers or coatings to improve dye fixation and durability. Natural dyes can be applied to textiles, followed by the use of environmentally friendly synthetic coatings to enhance colorfastness and ensure long-lasting vibrancy. These hybrid systems may offer a solution to the limitations of natural dyes, such as their relatively limited color range and lower fastness properties, while still maintaining a focus on sustainability.

Additionally, hybrid materials combining natural fibers, synthetic polymers, and bio-based additives can lead to the development of textiles with improved performance characteristics. This could include textiles with enhanced flame resistance, water repellency, or UV protection, all while maintaining a sustainable, eco-friendly production process. By integrating synthetic materials in a careful and deliberate manner, hybrid systems can significantly expand the potential of natural dyes and biomordants in the textile industry.

## 13 Recommendations for Future Research

Future studies should explore the development of biomordant-based dyeing technologies tailored to the diverse needs of the textile industry. This includes broadening the range of natural dye sources and biomordants to enhance the multifunctional properties of dyed fabrics, such as antibacterial, antioxidant, and UV-resistant effects. It is also important to assess the long-term durability and wash fastness of these functional properties under real-world conditions. Investigating the compatibility of biomordants with various fabric types, including synthetic blends, will further support their wider adoption. Additionally, identifying scalable and cost-effective processes suitable for industrial application is essential for commercial viability. Equally critical is the evaluation of the environmental impact of biomordant dyeing systems to ensure their alignment with sustainability goals. Strengthening biomordant dyeing technologies in these areas has the potential to drive sustainable innovation in the textile sector, meeting growing consumer demands for high-performance, health-conscious, and environmentally responsible products.

## 14 Conclusion

In conclusion, the exploration and advancement of natural dyes and biomordants represent a significant step forward in the pursuit of sustainability within the textile industry. As the demand for eco-friendly, nontoxic, and biodegradable alternatives to synthetic dyes and mordants continues to rise, the potential for natural sources to meet these needs has never been more evident. From the bioengineering of dyes and biomordants derived from microorganisms and plants to the application of cutting-edge nanotechnology, the research landscape is rich with innovation aimed at enhancing the functionality and performance of natural dyes.

The incorporation of microbial pigments, waste-derived colors, and bio-based mordants offers promising solutions that reduce the environmental footprint of dyeing processes while maintaining the desired aesthetics and durability of textiles. The synergy between biotechnology and materials science is opening new frontiers, allowing for the creation of textiles that are not only sustainable but also high-performance and versatile. Moreover, hybrid systems that combine the benefits of both natural and synthetic methods are offering pragmatic solutions to challenges such as colorfastness and dye yield.

Despite the impressive strides made, there are still challenges to overcome in scaling these technologies for large-scale industrial applications. Continued research into the optimization of natural dye production, the development of more efficient biomordants, and the refinement of hybrid systems is essential for ensuring that these innovations can meet the growing demands of the global textile market. As the industry moves toward more sustainable practices, the adoption of natural dyes and biomordants, supported by biotechnology and nanotechnology, will play a pivotal role in shaping the future of textile production.

In essence, the integration of natural dyes and biomordants into the textile industry offers an exciting opportunity to create a more sustainable, eco-conscious future, where the aesthetics, performance, and environmental impact of textiles are harmoniously balanced. The exploration toward this future will require collaborative efforts across disciplines, innovative thinking, and a commitment to sustainability—values that will define the next generation of textile production.

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### Statements and additional information

**Conflict of Interest** The authors declare that they have no conflict of interest.

**Authors Contributions** S.I., K.Z.M., A.M., M.A.S., S.B., M.R., S.H., M.A.M., and A.N.K.: Conceptualization, methodology, data analysis, and writing of the original draft; M.A.J.: Conceptualization, methodology, supervising, data analysis, editing, and reviewing.

**Data Availability** The authors declare that the data supporting the findings of this study are available within the paper.

**Ethical Approval** The findings are presented transparently, truthfully, and without any form of fabrication or improper data manipulation.

**Consent to Participate** All authors agree to continue to support the follow-up work.

**Consent for Publication** All authors have reviewed and approved the final version of this manuscript and consent to its publication. Each author confirms that the manuscript is an original work and has not been previously published nor is under consideration for publication elsewhere.

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