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Enhancing Textile Sustainability Through Natural Dyes: Performance on Wool and Wool Synthetic Blends

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ABSTRACT

Environmental concerns regarding the impact of textile dyeing have stimulated research into the development of natural dyes as sustainable alternatives to synthetic dyes. This study presents a comprehensive analysis of the scientific literature on the application of natural dyes to wool and wool-synthetic fiber blends subtract, focused on the interaction between natural dyes and wool and synthetic fibers, mordant-assisted dyeing processes, and dyeing performance parameters, including dye uptake, fastness properties, and color uniformity. Wool fibers, with their protein structure containing different reactive functional groups, exhibit a greater affinity for natural dyes than synthetic fibers, resulting in greater dye absorption and also better color intensity and fastness. Synthetic fibers, on the other hand, have limited affinity for natural dyes and, consequently, exhibit heterogeneous dye distribution and less color uniformity. Optimized natural dyeing processes, using natural dyes with the combination of specific mordant agents, included the use of bio-mordants, can significantly improve dye fixation on yarns and fabrics, color strength, and fastness properties. However, industrial application of natural dyes has some limitations related to color variability and reproducibility, as well as scalability of the dyeing process. The present work proposes a comparative framework to evaluate the performance of natural dyes for dyeing fabrics made from wool and wool-synthetic blends, facilitating the selection of materials and dyeing process parameters. The development of dyeing processes that use natural dyes, combined with bio-based mordants, can contribute to more sustainable textile practices.

Keywords: Natural dyes, Wool fibers, Wool-synthetic blends, Sustainable dyeing

INTRODUCTION

The dyeing process is considered one of the stages with the greatest environmental impact in the textile product life cycle, due to its intensive consumption of water, energy, and the use of chemicals (Holkar et al., 2016). Furthermore, the large volumes of effluents generated by the dyeing process,

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which contain residual dyes, salts, and recalcitrant organic compounds, lead to high chemical oxygen demand (COD), biochemical oxygen demand (BOD), and significant ecotoxicity (Holkar et al., 2016; Yaseen & Scholz, 2019; Castro et al., 2019). The environmental impact of dyeing is related to the extensive use of synthetic dyes, which are widely used in industrial applications due to their higher color performance and reproducible coloration. The molecular structure of synthetic dyes is often based in aromatic structures and, azo linkages (–N=N–), which make them resistant to biodegradation and lead to environmental persistence (Robinson et al., 2001). An incomplete degradation can generate toxic intermediates, such as aromatic amines. The use of auxiliary chemicals during dyeing, particularly in pre- and post-treatment processes, further increases the environmental impact (Pinheiro et al., 2004; Kavitha et al., 2025).

Recently, natural dyeing has emerged with a viable alternative to the use of synthetic dyes for more sustainable textile dyeing processes. Extracted from biological sources, plants, insects, and microorganisms, natural dyes are usually biodegradable and have low toxicity, reducing the environmental impact associated with the dyeing processes (Fried et al., 2022; Islam et al., 2025). Certain natural dyes can impart functional properties to textile fibers, such as antimicrobial activity and UV protection, particularly in protein-based fabrics (Repon et al., 2023). However, several technical limitations still restrict their widespread industrial application. Natural dyes generally exhibit lower dye uptake and poor fastness resistance properties on textile substrates when compared to synthetic dyes and usually require the use of mordant agents or pre-treatments to improve dye uptake by the fibers (Zhang et al., 2022; Repon et al., 2024). The use of bio-mordants, enzymatic treatments, and assisted dyeing technologies, such as microwave and ultrasound, can improve the affinity between the dye and the fibers (Eyupoglu et al., 2024; El-Bassuony et al., 2025).

Wool and wool–synthetic blends are important substrates for natural dyeing applications. Differences in dye uptake and dyeing process conditions between wool and synthetic fibers increase the complexity of the dyeing process for wool–synthetic fiber blends, often requiring optimized or multi-stage dyeing processes (Lewis, 2014; Burkinshaw, 2016). When using natural dyes, whose interaction mechanisms differ from those of conventional synthetic systems, the differences between wool and synthetic fiber properties become particularly important.

Although natural dyeing has been extensively investigated for individual textile substrates, particularly wool, limited attention has been given to the systematic comparison between dyeing of pure wool and wool–synthetic blend systems.

This study provides a comprehensive review of the application of natural dyes in wool and wool–synthetic blend systems. The analysis of the scientific literature focuses on dyeing behavior, dye-fiber interactions, mordanting strategies, and dyeing performance indicators. An integrated framework is also proposed for comparing and evaluating dyeing performance in natural dye systems, contributing to increased sustainability in textile dyeing.

NATURAL DYEING IN TEXTILE SYSTEMS

Natural Dyes: Properties and Sustainability

Natural dyes are derived from renewable biological sources, including plants, insects, and microorganisms, with plant-based dyes representing the most widely used class in textile applications (Fried et al., 2022; Pizzicato et al., 2023). They are chemically characterized by the presence of compounds with chromophoric and bioactive properties, such as polyphenols, flavonoids, tannins, and anthocyanins. These natural compounds contain functional groups (e.g., hydroxyl and carbonyl groups) that promote interactions with the functional groups of textile fibers. For protein fibers like wool, the amino ($–NH_2$) and carboxyl (–COOH) functional groups enable hydrogen bonding, ionic interactions, and coordination complex formation with those of the natural dye molecules, resulting in enhanced dye uptake (Pizzicato et al., 2023; Adeel et al., 2022). Conversely, synthetic fibers lack these reactive functional sites, resulting in significantly lower dye uptake of natural dyes.

The application of natural dyes in the dyeing of textile substrates offers several environmental advantages compared to synthetic dyes, such as biodegradability, lower toxicity, and reduced environmental persistence (Fried et al., 2022; Kavitha et al., 2025). Recent studies have further highlighted the potential of agro-industrial residues and biomass waste—such as fruit peels, bark, and agricultural by-products—as cost-effective and sustainable sources of dyes, supporting circular economy principles (Basto et al., 2025; Correa et al., 2025)."

Limitations and Challenges

Natural dyeing has several technical challenges and operational constraints that restrict its application in an industrial scale. One of the primary challenges is the lack of consistence of raw materials from which natural dyes are extracted. The composition of plant-based dyes depends on several factors such as plant species, geographic origin, and extraction conditions of dyes. Variations in the chemical composition of a given natural dyes lead to inconsistencies in color strength and dyeing reproducibility, which makes the standardization of natural dyeing difficult processes for industrial applications (Pizzicato et al., 2023). Another key limitation is related to color fastness as natural dyes generally have moderate to low fastness to washing, light exposure, and rubbing due to their susceptibility to degradation processes such as photodegradation and oxidation (Zhang et al., 2022; Pizzicato et al., 2023). However, optimizing dyeing conditions, mordant selection, and mordanting procedures for a given dye/mordant combination and fiber composition can lead to improved dyeing performance. For example, Gözütok and Bahtiyari (2022) reported enhanced light fastness in wool dyed with pomegranate-based dyes when process parameters were optimized, while Adeel et al. (2022) showed improved performance using bio-mordants. Natural dyeing is also sensitive to process parameters such as pH and temperature, requiring the precise control of process conditions to ensure consistent dyeing performance.

Industrial scalability also remains a big significant barrier. Limited availability of raw material for natural dyes, low extraction efficiency, and high processing variability contributed to large production costs compared to synthetic dyeing systems (Karadag, 2022; Elsahida et al., 2019).

DYE–FIBER INTERACTION AND SYSTEM COMPLEXITY

Interaction Mechanisms

Dye–fiber interaction depends on the chemical composition of the dyes and fibers substrates and determines the affinity of a given dye for a type of fiber. For protein fibers such as wool, dye–fiber interactions are governed by the keratin functional groups present at fiber surface, including the amino ($-NH_2$) and carboxyl (–COOH) groups. These functional groups enable different chemical dye–fiber interaction mechanisms, namely through ionic interactions, hydrogen bonding, and coordination complex formation (Rippon, 2013; Islam et al., 2025). Natural dyes rich in polyphenolic compounds (e.g. tannins and flavonoids) extracted from plant-based sources exhibit high affinity for wool fibers through the formation of stable interactions with functional groups in wool keratin (Tian et al., 2022). Phenolic hydroxyl groups in dye compounds contribute to hydrogen bonding, while ionizable groups in wool keratin, such as amino ($-NH_2/-NH_3^+$) and carboxyl ($-COOH/-COO^-$), facilitate ionic interactions under controlled pH conditions.

Synthetic fibers such as polyester are characterized by a hydrophobic structure, low surface energy, low moisture regain, high crystallinity, compact molecular packing, limited free volume, and low availability of accessible functional groups, which restrict dye diffusion and dye–fiber interactions. Consequently, in the dyeing of synthetic fibers with natural dyes, it is often necessary to apply treatments to functionalize the surface of the materials to be dyed, including mordanting, cationization, and enzymatic modifications, along with optimized or more severe dyeing conditions, in order to improve dye absorption and dye-fiber affinity (Zhang et al., 2022).

Influence of Process Parameters

Dyeing performance is strongly influenced by several process parameters, including the pH of the dye bath and the dyeing temperature. The pH is an important parameter related to the degree of ionization or protonation state of functional groups in the fiber substrate and dye molecules. In the dyeing of wool fibers, slightly acidic baths (pH 4–5) will promote the protonation of amino groups which enhances the electrostatic fiber–dye interactions with anionic dyes, increasing the dye uptake (Shore, 2002). The dyeing temperature has influence on the diffusion of dyes molecules and fiber swelling behavior. Rising the dyeing temperature will increase dye molecular mobility, which increases diffusion and facilitates their penetration into textile substrates; however, excessively high temperatures can lead to the degradation of temperature-sensitive natural dyes (Pizzicato et al., 2023). The dyeing time and liquor ratio of the dye bath (bath-to-fabric ratio) largely influence the chemical equilibrium state during dyeing and, therefore, also the degree of dye absorption by the textile fibers. The application of pre-treatment processes, including enzymatic treatments or fiber surface modification techniques, can further improve dye absorption and dye–fiber interactions, particularly in synthetic or blended systems, where intrinsic low reactivity limits dye uptake (Zhang et al., 2022; El-Bassuony et al., 2025).

Role of Mordants

Natural dyes are usually applied in combination with mordant agents to enhance dye fixation and color fastness. Mordants, which are conventionally water-soluble metal salts, improve the formation of coordination complexes between dye molecules and fiber functional groups, thereby increasing the dye affinity to fibers and the colorfastness properties of dyed fabrics (Islam et al., 2025). The metallic mordants that are largely used in the dyeing of textiles, such as alum (potassium aluminum sulfate) and iron salts, are very effective in mordanting processes because they can form stable metal–dye–fiber interactions. However, the metal ions that are released into dyeing effluents have toxic effects on human health and ecotoxicological impacts on the environment. For this reason, the use of bio-mordants derived from natural sources, including tannin-rich plant extracts, other polyphenol-rich natural extracts, and biopolymers such as chitosan, have been investigated as alternatives to the traditional metallic mordants, allowing for a comparable dye uptake efficiency while significantly reducing the dyeing environmental impact (Adeel et al., 2022; Islam et al., 2025).

Mordanting process efficiency depends not only on the process parameters, but also on the mordant agents used, mordant concentration, and the application method (pre-, meta-, or post-mordanting), which directly influence dye uptake, color strength (*K/S*), and color uniformity.

Challenges in Dyeing Wool Versus Wool-Synthetic Blends

The natural dyeing in fiber blends with natural and synthetic fibers can be technologically challenging. Wool–synthetic blends involve fibers with a big different physical and chemical properties, resulting in differential dye uptake and posing significant challenges for achieving color uniformity and fastness resistance. Natural dyes exhibit high affinity for wool fibers and low affinity for synthetic fibers, which results in larger dye uptake by wool fibers compared with the synthetic ones, consequently, heterogeneous color distribution is observed in dyed blended fabrics. Addicionally, differences in diffusion kinetics contribute to uneven dye penetration in blended fabrics (Zhang et al., 2022).

The optimal dyeing conditions for each type of fiber are different, as they depend on the fiber's chemical composition, morphology, and dye–fiber affinity. The dyeing of wool fibers, involving ionic and hydrogen bonding interactions, requires moderate temperatures and acidic conditions whereas the dyeing of synthetic fibers, such as polyester, requires higher temperatures and relies on different interaction mechanisms. Multi-stage dyeing processes required for wool–synthetic fiber blends, involving different process parameters, increases complexity of the dyeing process and the resource consumption (Lewis, 2014; Burkinshaw, 2016).

Recent studies, including fiber surface modification and advanced dyeing technologies, aim to improve dyeing compatibility and enhance dye diffusion and uptake in blended systems (Zhang et al., 2022; Yiğit, 2026). However, further optimization is still required to ensure the effective application of natural dyes in more complex textile structures.

COMPARATIVE PERFORMANCE ANALYSIS

Performance Indicators

The evaluation of dyeing performance in textile systems is based on key parameters that reflect dye uptake efficiency and durability. The most relevant indicators include dye uptake, color strength (*K/S*), fastness properties, and color uniformity or levelness (Pizzicato et al., 2023; Repon et al., 2024).

Dye uptake quantifies the extent of dye exhaustion from the dye bath and its adsorption onto the textile substrate and is governed by dye–fiber interactions that determine the dye adsorption and the diffusion of dye within the fiber structure. The wool fibers exhibit higher dye uptake due to the presence of ionizable functional groups and stronger dye–fiber interactions, whereas synthetic fibers show lower dye uptake due to their lower reactivity and reduced dye–fiber interactions (Zhang et al., 2022; Kovačević et al., 2021).

Color strength is evaluated using the Kubelka–Munk function (*K/S*) and it provides a quantitative measure of the intensity of color. *K/S* values are calculated from the optical diffuse reflectance of the dyed material as the ratio of the absorption coefficient (*K*) to the scattering coefficient (*S*). Dyed wool substrates using natural dyes can have adequate *K/S* values, particularly under optimized dyeing and mordanting conditions. Tian et al. (2022) reported that plant-derived dyes containing phenolic compounds exhibit high affinity for wool fibers, leading to high dye absorption and good color intensity (*K/S*) under appropriate process conditions combined with metallic mordanting.

Fastness properties, including color fastness to washing, light, and rubbing, are used to evaluate the resistance of dyed textiles to color change and color transfer over time. Natural dyes generally exhibit relatively low color fastness, particularly to light, because of photodegradation of the dye molecules (Pizzicato et al., 2023). However, the application of bio-mordants and optimized dyeing conditions has been reported to significantly enhance color stability and improve color fastness, particularly to washing and light, in wool textiles dyed with natural dyes (Adeel et al., 2022; Gözütok and Bahtiyari, 2022). A comparative study on dyeing wool, cotton, and lyocell fabrics with natural dyes have shown that color strength and color fastness performance are strongly influenced by fiber composition and mordant selection (Ostheim et al., 2026).

Color uniformity (levelness) depends on the uniform distribution of dye throughout the textile substrate and is an import parameter for industrial applicability of natural dyes. In fiber blends, differences in dye uptake between fiber components and variations in dyeing conditions result in non-uniform coloration (poor levelness) (Repon et al., 2024).

Wool vs. Wool Synthetic Blends Comparison

The performance of natural dyeing systems is strongly influenced by fiber type, dye chemistry, and mordanting conditions. The wool and synthetic fibers in wool–synthetic blends exhibit significant differences in dyeing behavior, including dye uptake and affinity. Natural dyes have a high affinity for wool fibers, resulting in enhanced dye uptake. Consequently, 100% dyed wool substrates exhibit high color strength (*K*/*S*) and good color uniformity (Tian et al., 2022; Kovačević et al., 2021). The lower dyeing performance commonly observed in natural dyeing of wool- synthetic blends is associated with differences in fiber chemistry, dye–fiber interactions, and the incompatibility of their optimal dyeing conditions. In the natural dyeing of wool–synthetic blends, these differences often result in uneven dye distribution, reduced color uniformity, and greater variability in fastness performance when compared to 100% wool substrates (Zhang et al., 2022).

PROPOSED FRAMEWORK FOR DYE PERFORMANCE EVALUATION

Framework Definition

A comparative framework is proposed in this work to evaluate the performance of natural dyes in the dyeing of 100% wool and wool–synthetic blend textiles. The framework incorporates technical indicators of dyeing performance, process-related parameters, and environmental criteria to support the systematic evaluation of natural dyeing systems. The use of key indicators of dyeing performance, including dye uptake, color strength (*K*/*S*), color uniformity, fastness properties, and process-related parameters, together with environmental indicators, provide a comprehensive evaluation of the performance of natural dyeing in wool and wool–synthetic blend systems. Enabling a systematic comparison between both textile systems, the framework facilitates the identification of key limitations and supports the selection of appropriate material combinations and dyeing parameters to improve a natural dyeing performance and sustainability outcomes.

Performance Evaluation of Wool and Wool–Synthetic Blends

The framework allows for a direct comparison of natural dyeing performance in wool and wool–synthetic blend systems (Table 1). Wool fibers exhibit superior dyeing performance with natural dyes due to the presence of reactive functional groups present in keratin, whereas wool–synthetic blends present limitations related to differences in fiber chemistry and incompatibility of optimal dyeing conditions, leading to differential dye uptake between wool and synthetic fibers and uneven dye distribution between these fibers.

Table 1: Evaluation of the natural dyeing of wool and wool–synthetic blend systems.

Parameter	Wool Fibers	Wool–Synthetic Blends
Color strength (*K/S*)	High	Moderate to low
Dye uptake efficiency	High	Heterogeneous / reduced
Fastness properties	Moderate to good (with mordants)	Variable / generally lower
Color uniformity	Good	Poor to moderate
Process complexity	Moderate	High
Environmental performance	Favorable	Process-dependent

Limiting Factors and Optimization Strategies

The proposed framework allows for the identification of the main factors that affect the performance of natural dyeing in wool–synthetic blend systems, which can be classified as material-, process-, and performance-related factors. Material-related factors include the low chemical reactivity of synthetic fibers and the variability in the composition of natural dyes. Process-related factors include differences between optimal dyeing conditions and fiber requirements and the limited dye diffusion. Performance-related factors include reduced fastness properties of the dyed synthetic in fiber blends, poor process reproducibility, and non-uniform coloration (levelness). To improve the performance of natural dyeing in wool–synthetic blend systems, several strategies can be implemented, including the optimization of natural dyeing conditions, the use of bio-mordant agents and fiber modification to improve dye uptake, and the application of advanced or hybrid dyeing technologies.

CHALLENGES AND FUTURE DIRECTIONS

The application of natural dyes at industrial scale is hindered by several technical and operational limitations including: the variability in the composition of natural dye; the limited reproducibility of dyeing results; the low compatibility with synthetic fibers, and the issues associated with the dyeing of wool–synthetic blends. These material- and process-related factors lead to inconsistent dyeing performance, reduced color uniformity, and lower fastness properties compared to conventional synthetic dyeing methods (Pizzicato et al., 2023; Repon et al., 2024). The availability of natural dyes depends of seasonal and geographical factors, and the extraction processes can be inefficient and produce variable results, increasing production costs and hinder large-scale industrial adoption of natural dyeing (Karadag, 2022; Elsahida et al., 2019). Natural dyeing of wool and synthetic fiber blends requires careful control of dyeing conditions, such as pH, temperature, and optimization of mordant conditions, which makes the process more complex.

Future research on natural dyeing should focus on improving dye-fiber compatibility and the reproducibility of dyeing performance/process. Promising research directions include the development of bio-based mordants to improve dye fixation with less environmental impact (Islam et al., 2025), as well as advanced dyeing technologies, such as supercritical CO2 and enzymatic processes, to improve dye yield and stability (Yiğit, 2026), which are already being applied, but more on a laboratory scale. Biotechnological production of natural pigments also opens new perspectives for improving the consistency and scalability of dye sources (Fried et al., 2022; Basto et al., 2025). Furthermore, developing strategies to improve the compatibility between natural dyes and synthetic fibers is essential, particularly in the dyeing of blended materials, such as wool and blends, a common mixture in clothing. Integrating natural dyeing into a circular economy model, including the recovery of agro-industrial waste, represents the fundamental path to improving sustainability and resource efficiency.

CONCLUSION

This study presents natural dyes as sustainable alternative to synthetic dyes, particularly for wool, by analyzing dye–fiber interactions, dyeing process parameters and performance evaluation of natural dyeing in wool and wool–synthetic blends. The results showed that wool fibers consistently achieve high dye uptake and color strength (*K*/*S*), good colorfastness performance and uniform coloration results. In contrast, natural dyeing of wool–synthetic blends present clear limitations related to the different properties of wool and synthetic fibers, including different dye uptake between the two types of fibers, low affinity with synthetic fibers, and incompatible processing conditions, which results in reduced color uniformity and variable colorfastness performance. Natural dyeing of fiber blend systems requires optimized dyeing conditions, effective mordanting procedures, and improved compatibility with synthetic fibers.

The main contribution of this study is the proposed framework used to compare and evaluate the performance of natural dyes in dyeing of wool and wool–synthetic fiber blend systems. This framework allows for a direct comparison of natural dyeing performance, improving material selection and process conditions on natural dyeing systems, which can lead to more efficient and sustainable processes to dye textile substrates.

The use of natural dyes in combination of bio-mordants demonstrates great potential for making industrial textile dyeing processes more sustainable. However, industrial scale adoption faces limitations related to raw material variability, reproducibility of coloration results, and scalability of the dyeing process.

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