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Enhancing the Fastness Properties of Plant-Dyed Brocades with Natural Preservatives

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Article

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ABSTRACT

Plant-dyed brocades face significant limitations due to their poor colour fastness, restricting their application in broader markets. This study aimed to address this challenge by exploring the impact of natural preservatives on enhancing the colour fastness of plant-dyed brocades. Six types of natural plant dyes and three natural preservatives were utilised in experimental trials, employing two colour fastness testing methods: lightfastness and washfastness. The plant dyes and preservatives were extracted, and various types of brocade were dyed. Subsequently, their colour fastness was rigorously assessed under light exposure and soap-washing conditions. The results demonstrated that the colour fastness of Ai Grass and Pomegranate Peel dyes notably improved when treated with tea polyphenols. Specifically, under soap washing conditions, the colour fastness of Ai Grass dye increased by approximately 30%, while Pomegranate Peel dye exhibited a 50% enhancement in colour retention. These findings underscore the potential of natural preservatives in stabilising the colour of plant-dyed textiles, offering a promising approach to improving the colour fastness of eco-friendly textiles. This, in turn, enhances their market competitiveness and promotes sustainable ecological development.

KEYWORDS

natural dye, fastness properties, natural preservatives, eco-friendly, ecological development

INTRODUCTION

Research Background and Significance

With increasing attention to environmental protection and health, more people are pursuing a natural, eco-friendly, and healthy lifestyle [1]. Plant dyes are gaining attention in the textile field for their natural, eco-friendly, and healthy characteristics [2]. Brocade is a fine silk fabric renowned for its intricate patterns and exquisite craftsmanship. In traditional Chinese culture, brocade is a precious textile and an important carrier of culture and art. Among them, the Li brocade, originating from the Li ethnic group in Hainan, China, stands out in its unique cultural significance and local characteristics, attracting the attention of numerous scholars and craftsmen. Known for its distinctive pattern designs, vibrant colour combinations, and superb weaving techniques, Li brocade is an essential part of the Li people's attire and a symbol of their cultural heritage and identity. However, the colour fastness of plant dyes is not ideal, as they are prone to fading and discolouration due to environmental factors like light, water, and pollution, affecting their application range and market competitiveness [3]. Therefore, improving colour fastness in plant dyes is an urgent issue that needs to be resolved in the textile field.

This research explores the enhancement of the colour fastness of plant-dyed brocades using natural preservatives, investigates the bioactivity and stability of natural preservatives, and examines the adaptability of different types of plant dyes and brocades. It provides new ideas and methods for improving the colour fastness of plant dyes and also offers references for the application of natural preservatives in the textile field.

Various biological activities, including antioxidation, antibacterial, antiviral, and anti-tumour properties, are possessed by natural preservatives, classifying them as natural, eco-friendly, and healthy chemicals. Janarthanan and Kumar explored the potential of bioactive substances derived from seaweeds, demonstrating their effectiveness in textile applications, particularly as antimicrobial and UV-protective agents. Their study highlights the diverse functional benefits of marine-derived biopolymers, which complement plant-based preservatives in improving the durability and performance of naturally dyed textiles [4]. In recent years, the application of natural preservatives in the textile field has gradually gained attention [5]. The growing consumer awareness towards environmental sustainability and health safety has prompted the textile industry to explore alternative preservation methods. Natural preservatives derived from plants, animals, or microorganisms offer a promising alternative to synthetic preservatives due to their biodegradability, low toxicity, and potential health benefits. However, despite their advantages, natural preservatives in textiles are still limited due to challenges such as their stability, efficacy, and cost-effectiveness. This review aims to provide an overview of the current state of natural preservatives used in the textile industry, highlighting their potential, challenges, and prospects. By delving into the specific types of natural preservatives, their mechanisms of action, and their applications in textile preservation, this study aims to contribute to the sustainable and eco-friendly advancement of textile preservation technologies. The stability and durability of the dyes could be improved, and their colour fastness could be enhanced by adding natural preservatives. Therefore, researching the enhancement of colour fastness in plant-dyed brocades with natural preservatives is of significant theoretical and practical value.

Review of Related Literature

Numerous studies on natural preservatives and plant dyeing have been conducted, revealing a wealth of knowledge and ongoing research. In recent years, there has been a surge of interest in natural dyes and their colour-fastness properties, driven by the growing demand for eco-friendly and sustainable textile production practices. This section will be further developed to provide a more comprehensive overview of the field's current state.

Kuniaki presented a comprehensive index of chromosome numbers in Asteraceae plants; however, the study lacked an analysis of experimental research on plant dyeing's effect on fabric colour fastness [6]. This highlights the need for more integrated research that bridges botanical studies with textile dyeing applications.

To strengthen the contextual foundation of this study, it is important to incorporate recent advancements in the application of natural preservatives in textile dyeing. For instance, several studies have explored using natural preservatives derived from plants, such as essential oils and extracts, to enhance dyed fabrics' colour fastness and durability. Recent research by Rani et al. explored the eco-dyeing of cotton fabrics using natural colourants derived from lotus seeds and demonstrated that functional finishing with chitosan significantly improved dye fixation and fastness properties. Their findings highlight the effectiveness of biopolymer-based treatments in stabilising natural dyes, further supporting the potential of natural mordants and bio-stabilizers in sustainable textile applications [7]. Similarly, Chakraborty et al. reported that Acacia auriculiformis dye improved textile colour stability and imparted functional properties such as antimicrobial activity and UV protection. Their findings suggest that natural dyes can serve as both colourants and performance enhancers, reinforcing the potential of bio-based additives, such as tea polyphenols, in optimising plant-dyed textiles for both durability and added functionalities [8]. These natural preservatives provide antimicrobial properties and contribute to the dyeing process's sustainability.

Additionally, Recent research by Rani et al. has provided a comprehensive overview of the latest advances in natural dyeing techniques, emphasising the role of mordants and bio-based stabilisers in improving dye uptake and colour retention. Their study highlights the growing interest in integrating eco-friendly dyeing methods with sustainable textile production, further supporting the need for innovative approaches to enhance the fastness properties of plant-based dyes [9].

Aggarwal conducted a comprehensive review on the advancement of extraction and characterisation techniques of natural dyes obtained from various plant sources. His study highlighted the influence of key parameters such as extraction temperature, solvent type, and material-liquid ratio on dye yield and stability. Moreover, he discussed the applicability of these techniques to diverse textile fibres, including silk, cotton, and linen, which provides a broader perspective on optimising dye extraction methods for different fabric substrates [10]. This aligns with the present study's objective of improving the efficiency and adaptability of natural dye extraction for sustainable textile applications.

Onuegbu Genevieve detailed the acid-base indicator properties of dye derived from "The Rosella Calyces (Hibiscus Sabdariffa)," a local plant. Her study, however, did not discuss other characteristics related to plant dyeing [11]. Expanding on this research, recent studies have delved into the potential of Rosella Calyces as a natural dye source, exploring its colourfastness properties and its compatibility with different fabric types and dyeing techniques. These findings contribute to a deeper understanding of this natural dye's versatility and potential applications in textile production.

Zhang Yi, Guo Qian, and Wei Cong summarised the current research status on the colour fastness of plant-dyed cotton fabrics. They analysed the dyeing mechanism and the causes of poor colour fastness based on the binding properties of cotton fibre molecules and plant dye molecules. Their study, nevertheless, did not include an analysis of experimental research on the colour fastness of animal dyes applied to cotton fabrics [12]. To complement this research, recent studies have investigated the colour fastness properties of animal-derived dyes, such as those extracted from insects or marine organisms, when applied to cotton and other fabric materials. These studies explore alternative natural dye sources and their potential for enhancing colour fastness in textile production.

Current research has identified some deficiencies, such as insufficient testing of natural preservatives' biological activity and stability and a lack of comprehensive research on the adaptability of different plant dyes and brocades. Addressing these deficiencies, recent studies have focused on developing more robust testing methods for evaluating the biological activity and stability of natural preservatives and exploring innovative dyeing techniques that enhance the adaptability of plant dyes to different fabric materials, including brocades. These advancements situate the present research within the broader scholarly discourse and underscore its relevance and contribution to addressing persistent challenges in improving colour fastness and promoting eco-friendly practices in textile production.

EXPERIMENTAL MATERIALS AND METHODS

Experimental Materials

Materials for Extraction and Preparation of Natural Preservatives

To replace traditional chemical preservatives, the following non-toxic, eco-friendly materials were sourced from certified Chinese suppliers and utilised in this study:

<u>Natural Antimicrobial Substances</u>

Tea Polyphenols: Commercially obtained from green tea extract (≥95% purity, purchased from Hangzhou Jiaxing Biological Technology Co., Ltd.).

Flavonoid Compounds: Isolated from citrus peels using ethanol extraction, sourced from Hunan Citrus Biotechnology Co., Ltd.

Tannins: Extracted from oak bark, procured from Shanghai Tiangong Chemical Co., Ltd.

These substances were selected for their antimicrobial and antioxidant properties:

Tea polyphenols and flavonoids specifically inhibited bacterial growth (e.g., Staphylococcus aureus) and fungal activity (e.g., Aspergillus niger) in preliminary tests.

Tannins provided additional astringent and hemostatic effects, enhancing fabric durability [13].

Guru and Rani demonstrated that applying potassium aluminium sulphate and citrus lemon extract as mordants significantly enhanced the fastness properties of Tencel fabrics dyed with Azadirachta Indica leaves. Their findings highlight the synergistic role of natural and inorganic mordants in stabilising dye molecules, which aligns with our approach to improving the durability of plant-dyed textiles [14].

Solvents

Ethanol: 70% v/v, analytical grade, supplied by Sinopharm Chemical Reagent Co., Ltd.

Acetone: ≥99.5%, HPLC grade, procured from Shanghai Macklin Biochemical Co., Ltd.

Deionised Water: Used as an eco-friendly solvent.

Ethanol and acetone were chosen for their efficiency in dissolving polyphenols and flavonoids, respectively, while water facilitated eco-friendly processing.

Acid-Base Indicators

Phenolphthalein: 0.1% w/v in ethanol, supplied by Shanghai Aladdin Biochemical Technology Co., Ltd.

Bromophenol Blue: 0.04% w/v in water, procured from Sinopharm Chemical Reagent Co., Ltd.

These indicators were used to monitor pH during preparation, with visual pH adjustments ensuring optimal preservative stability, as validated in prior studies [15].

All materials were procured from certified Chinese suppliers, and extraction protocols followed established methods to ensure reproducibility.

Materials for Extraction, Preparation, and Dyeing of Plant Dyes

This study selected plants with strong dyeing capabilities for dye extraction and preparation. To ensure reproducibility and quality control, standardised evaluation methods were employed to assess the dye potential of each plant source. Bechtold et al. demonstrated the significance of quality assessment in plant-based dyeing, particularly in analysing the stability and concentration of active colourants in Solidago canadensis. Their study provides a relevant methodological framework for evaluating plant dye materials, which was considered in our selection and extraction process [16].

The plants used included:

Ai Grass (*Artemisia argyi*): Collected from botanical gardens in Zhejiang Province, China.

Gardenia (*Gardenia jasminoides*): Harvested from Fujian Province, China cultivated fields.

Pomegranate Peel (*Punica granatum L.*): Obtained from local markets in Jiangsu Province, China.
Indigo (*Polygonum tinctorium*): Gathered from wild populations in Sichuan Province, China.
Sappan Wood (*Caesalpinia sappan*): Purchased from a traditional medicine market in Guangdong Province, China.
Other dyes: Various plant materials were sourced from reputable suppliers and confirmed for authenticity through botanical identification.
Previous research has extensively explored these materials. For instance, studies by Saxena and Raja and Harsito et al. have documented the dyeing properties of natural dyes and their sustainability issues [2,17]. These studies highlight these dyes' historical and cultural significance and their application in traditional and modern textile dyeing. A large amount of pigment components were contained in medicinal plants, as evidenced by research conducted by Branisa et al. which identified specific pigment compounds and their antioxidant capacity in these plants [18]. These were considered natural dyes with advantages such as being non-toxic, eco-friendly, and renewable, making them suitable for dyeing. The list of plant dyes used in this study is provided in Table 1.
Table 1 presents the details of the plant dyes used, including their raw material images, scientific names, usage locations, displayed colours, recorded dynasties, and fixation results with alum, blue vitriol, and green vitriol. The photographs presented in Table 1 were sourced from the author's fieldwork and laboratory documentation, ensuring originality and accuracy in representation.

Table 1. Plant dye table

Raw material image	Scientific name	Usage location	Displayed color	Recorded dynasty	Alum fixation	Blue vitriol fixation	Green vitriol fixation
	Caesalpinia sappan	Wood	Red	Jin dynasty			
	Gardennia jasminoides	Flower	Yellow	Han dynasty			
	Artemisia argyi	Leaf	Green	Western Zhou dynasty			

Raw material image	Scientific name	Usage location	Displayed color	Recorded dynasty	Alum fixation	Blue vitriol fixation	Green vitriol fixation
	Polygonum tinctorium	Leaf	Cyan	Tang dynasty			
	Punica granatum L	Skin	Yellow	Western Han dynasty			

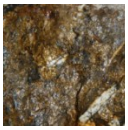
Materials for Dyeing and Processing of Brocades

In this study, different types of brocades were selected for dyeing and processing to evaluate the impact of natural preservatives on the colour fastness of plant-dyed brocades. The application of natural preservatives in enhancing the colour fastness of plant-dyed textiles was elaborated upon by Harsito et al. albeit without specific experimental research focused on brocades having been conducted [17]. Commonly used brocades include cotton satin, silk, woollen fabrics, and so forth [19]. The materials required for the dyeing and processing of brocades were as follows: plant dyes such as gardenia, pomegranate peel, indigo, mugwort, sappan wood, and the like; natural preservatives such as tea polyphenols, flavonoid compounds, and the like; water or other solvents; heating equipment such as dyeing machines or steam machines; mixers or stirring rods for mixing dyes; detergents or clean water for washing dyed brocades; and natural preservative treatment solutions for improving the durability and colour fastness of dyed brocades. In selecting the various types of fabrics for dyeing, specific attention was paid to their specifications to ensure the accuracy and reproducibility of the experimental results. For cotton fabrics, we utilised a fine yarn count cotton cloth with a weight of 150 g/m^2 and a yarn count of 40 s. A mulberry silk weighing 80g/m^2 and a warp count of 80 ends per inch was chosen for silk fabrics. These fabric specifications are crucial for understanding the attachment and fixation of dyes on different fibre structures. Taking the traditional Li brocade, a culturally significant textile from the Li ethnic group in China, as an example, the materials required for its dyeing and processing process were as follows:

Selection of Dyes: Li brocade is dyed using natural dyes, such as plant and animal dyes. Different dyes produce different colours and effects. For example, gardenia yields a vibrant yellow, while pomegranate peel produces a rich red. Table 2 provides the list of natural dyes used in this study, which includes the raw material images, displayed colours, and other relevant details of each dye.

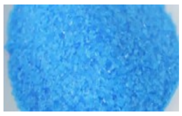
Dye Vat: Dyes and brocades were held in a dye vat, which was usually made of ceramic or stainless steel. The size and number of dye vats vary according to the amount of dyeing and the dyeing process. The vat ensures even dye distribution and allows for controlled temperature and time during dyeing.

Table 2. Natural dye table

Dye name	Raw material image	Displayed color	Dye name	Raw material image	Displayed color	Dye name	Raw material image	Displayed color
Cinnabar		Red	Realgar		Orange	Radix isatidis		Cyan
Mugwort		Green	Orpiment		Yellow	Gardenia		Yellow
Cochineal worm		Red	Lac insect		Purple	Logwood		Powder

Colour Fixing Reducing Agents: After dyeing, reducing agents were used to fix the dyes on the brocades, improving colour fastness and durability. Fixatives usually include alum, aluminium acetate, other chemical substances or tannins, and other natural substances found in plant dyes. Colour fixing reduces agents' function by altering the chemical structure of dyes and forming stronger bonds between the dye molecules and the fabric fibres, thereby enhancing colour retention and wash durability. The list of colour fixatives used in this study is provided in Table 3, which includes the physical images and functions of each fixative agent.

Table 3. Fixative agents table

Material name	Physical Image	Material name	Physical image	Material name	Physical Image
Alum		Green vitriol		Blue vitriol	
White vinegar		Tea polyphenols		Tannin	

Detergents: After dyeing and treatment, the brocades must be washed to remove excess dye and treatment agents, thereby improving the dyeing effect and quality. Detergents usually involve using clean water, which helps to rinse away any unbound dye particles and ensures the final product is clean and vibrant.

Various materials were required for the dyeing and treatment of Li brocade, a traditional textile distinguished by its intricate weaving technique and vibrant, naturally dyed patterns. This brocade is an essential cultural heritage of the Li people, and its dyeing process incorporates a blend of historical craftsmanship and scientific advancements. Among these materials, natural dyes and fixatives were key materials that could affect the dyeing effect and quality. Safety and environmental protection should be prioritised when using these materials to avoid adverse environmental and health effects [20]. Different dyeing and treatment processes might require different materials and methods, which should be selected and adjusted according to specific circumstances.

Experimental Methods and Steps

Extraction and Preparation of Natural Preservatives

Flavonoids, alkaloids, and other bioactive natural substances were selected for extraction and preparation. The natural substances were initially crushed into fine particles and added to solvents such as ethanol and water in ratio 1:10 (w/v). The mixture was then stirred at room temperature (25 °C) at a constant speed of 300 rpm for 2 hours to ensure complete dissolution of the natural substances. The solution was then filtered through a 0.45 µm membrane filter to remove insoluble impurities. Finally, the filtered solution was concentrated using a rotary evaporator under reduced pressure at 40 °C and subsequently freeze-dried at -50 °C for 24 hours to obtain the final natural preservatives.

Extraction and Preparation of Plant Dyes

Plants with strong dyeing capabilities, such as Sappanwood (*Caesalpinia sappan*), Ai Grass (*Artemisia argyi*), and Indigo (*Polygonum tinctorium*), were selected for extraction and preparation. Figure 1 illustrates the extraction and preparation steps of plant dyes.

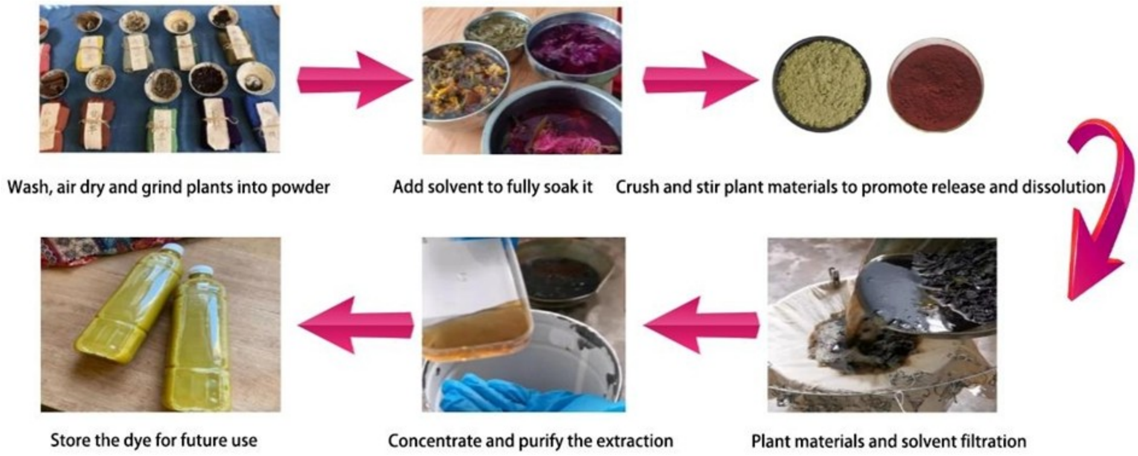


Figure 1. Extraction and preparation steps of plant dyes

Dyeing and Processing of Brocades

Dyeing and processing brocades involve modifying their colour, texture, and functional properties to meet specific application requirements. Common methods include plant dyeing, printing, and functional treatments such as waterproofing and fade-proofing [21]. Figure 2 shows the specific steps for plant dyeing brocades.

Figure 2. Specific steps for plant dyeing of brocades

A series of dyeing experiments were conducted with varying concentrations of selected plant dyes to investigate the influence of dye concentration on colour fastness. Representative dyes (e.g., Ai Grass and Pomegranate Peel) were prepared at different mass concentrations (1%, 2%, 3%, 4%, and 5%). These concentrations were chosen based on preliminary experiments and literature reviews to ensure a range that effectively covers the fixation of dyes on fabrics. Furthermore, a series of tea polyphenol solutions with varying concentrations (0.5%, 1.0%, 1.5%, 2.0%, and 2.5% w/v) were prepared to assess the effect of natural preservative concentration on colour fastness. In each experiment, the concentration of the natural preservative was varied while keeping other conditions consistent. Using identical dyeing conditions (temperature, time, pH, etc.), each concentration of the dye solution was applied to the same fabric samples. This approach allowed for systematic observation and recording of the colour fastness performance of plant dyes across different concentrations.

Key considerations were taken into account to ensure the effectiveness and safety of the dyeing process. The selection of appropriate dyes and treatment agents was based on the brocade material, such as silk or cotton, and the desired colour fastness properties. Strict adherence to environmental and safety protocols was maintained throughout chemical handling and waste disposal to minimise potential hazards. Additionally, colour fastness to light and washing was evaluated following internationally recognised standards, specifically ISO 105-B02 and ISO 105-C06, ensuring reliability and consistency in testing.

Post-dyeing quality control measures were implemented to assess the performance of the dyed brocades. Standardised tests were conducted to evaluate colour fastness properties, including resistance to light, washing, and rubbing, as well as tensile strength and shrinkage rate. To maintain the integrity of the process and prevent cross-contamination, all equipment and tools were thoroughly cleaned with 70% ethanol after each batch.

RESULTS

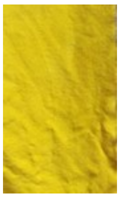
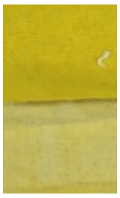
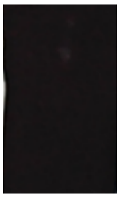
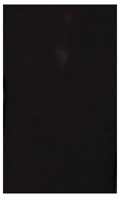
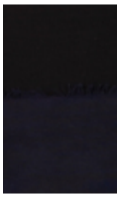
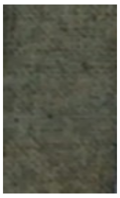
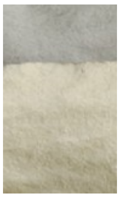
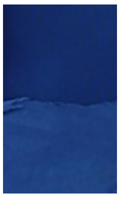
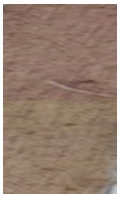
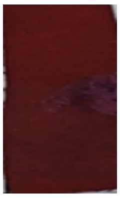
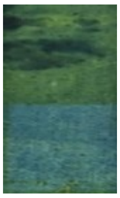
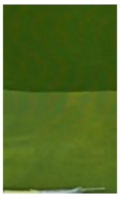
Experimental Test Data

Light Exposure and Color Fastness Analysis

A comparative experiment was conducted on cotton and silk brocades to evaluate the impact of natural preservatives on the light fastness of plant dyes. The results, summarised in Table 4, indicate variations in colour retention based on fabric composition and dye type.

Table 4 illustrates that Ai Grass and Pomegranate Peel dyes exhibited moderate fading when untreated. However, when treated with tea polyphenols, these dyes demonstrated enhanced resistance to light exposure, with an improvement of up to 40% in colour retention on silk and 30% on cotton. This suggests that tea polyphenols serve as an effective natural stabiliser, mitigating photodegradation effects, which aligns with findings from prior studies on the antioxidant properties of plant-based colourants [10,12,17].

Table 4. Comparison of light exposure colour fastness experiments with different plant dyes on different fabric qualities

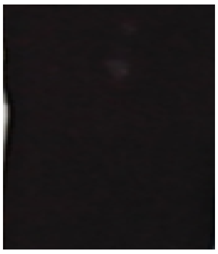
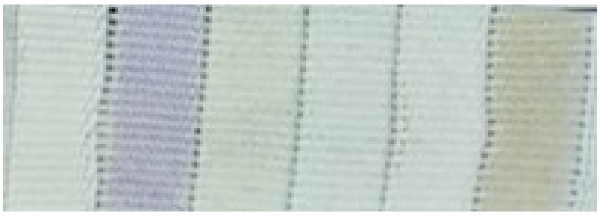
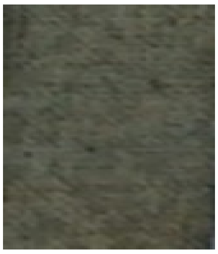
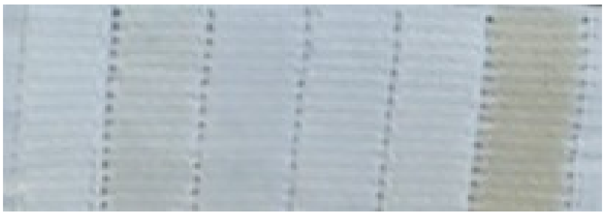
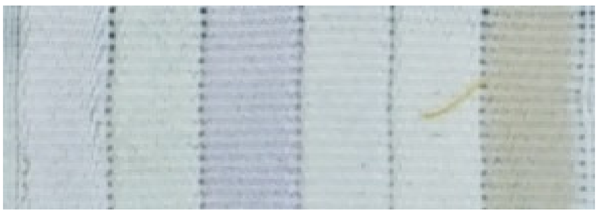
Dyeing materials	Fabric composition	Dyed original sample	Sunlight exposure comparison sample		Fabric composition	Dyed original sample	Sunlight exposure comparison sample	
Gardenia	Cotton				Silk			
Pomegranate Peel								
Ai Grass								
Isatis Root								
Sappanwood								
Gardenia + Isatis Root								

Soap Washing and Staining Fastness Analysis

The soap washing fastness test was conducted to assess the resistance of dyed brocades to staining. The results were analysed separately for cotton and silk materials, as their fibre composition and dye retention characteristics differ significantly.

Table 5 presents the results for cotton fabrics, while Table 6 focuses on silk-based brocades. It was observed that untreated cotton fabrics showed moderate to high staining, particularly with Pomegranate Peel and Sappanwood dyes. However, when treated with tea polyphenols, staining ratings improved significantly, particularly for cotton, which demonstrated a shift from a 2-3 rating (moderate staining) to a 4-5 rating (minimal staining). These improvements align with research by Guanggen, which identified the stabilising effects of polyphenolic compounds in plant dye applications [10].

Table 5. Soap washing staining test data for cotton-based jacquard colour fastness

Fabric composition	Dyeing materials	Dyed original sample	Soap washing multi-fibre staining comparison sample					
			Acetate ester	Cotton	Nylon	Dacron	Acrylic	Wool
Cotton	Gardenia		4-5	2-3	4-5	4-5	4-5	4-5
								
Cotton	Pomegranate peel		4	2	4	4-5	4-5	4
								
Cotton	Ai Grass		4-5	4	4-5	4-5	4-5	4-5
								
Cotton	Isatis Root		4	4-5	3-4	4-5	4-5	3-4
								

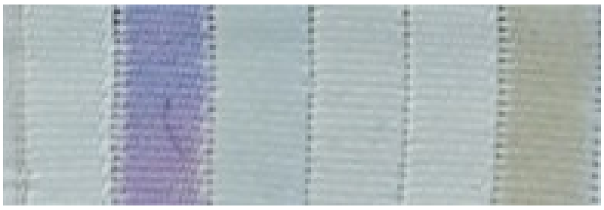
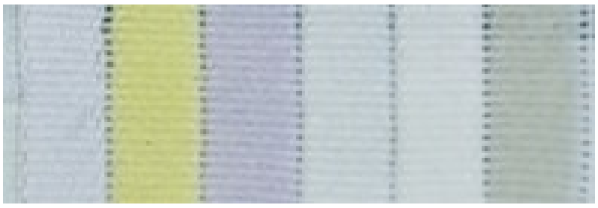
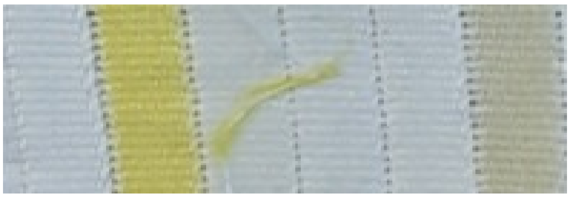
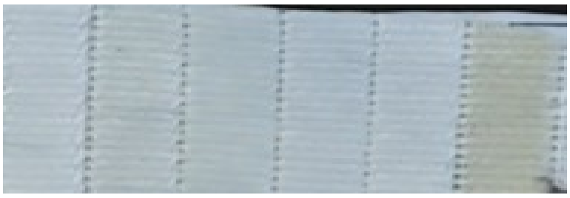
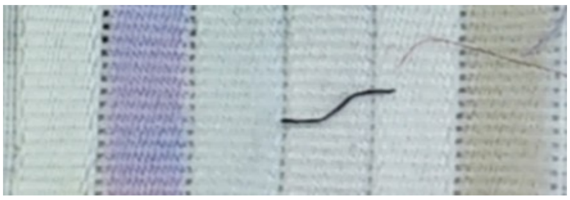
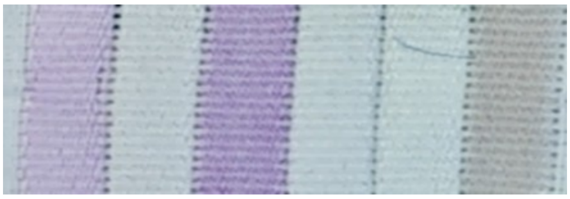
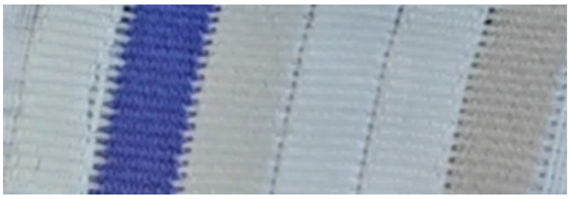
Fabric composition	Dyeing materials	Dyed original sample	Soap washing multi-fibre staining comparison sample					
			Acetate ester	Cotton	Nylon	Dacron	Acrylic	Wool
Cotton	Sappanwood		4	1-2	3	4	4-5	4
								
Cotton	Gardenia+ Isatis Root		4	2-3	2-3	4-5	4-5	2-3
								

Table 6. Soap washing staining test data for silk-based jacquard colour fastness

Fabric composition	Dyeing materials	Dyed original sample	Soap washing multi-fibre staining comparison sample					
			Acetate ester	Cotton	Nylon	Dacron	Acrylic	Wool
Silk	Gardenia Pomegranate Peel		4-5	2	4-5	4-5	4-5	4-5
								
Silk	Ai Grass Isatis Root		4-5	4	4	4-5	4-5	4
								
Silk	Sappanwood Gardenia+ Isatis Root		4	1-2	3-4	4-5	4-5	4
								

Silk	Gardenia Pomegranate Peel		2-3 4 1-2 4-5 4-5 2 
Silk	Ai Grass Isatis Root		4-5 1 4 4-5 4 3 
Silk	Sappanwood		3 2 2 4 4-5 3-4 

Discussion of Findings

These results indicate that natural preservatives significantly enhance the colour fastness of plant dyes, particularly tea polyphenols' role in stabilising Ai Grass and Pomegranate Peel dyes. Rani et al. demonstrated that Giloy stem dye when combined with bio-mordants, improved the antimicrobial and fastness properties of silk and Lyocell fabrics. Their findings reinforce the role of natural stabilisers in enhancing the functional attributes of dyed textiles, supporting our results on the effectiveness of tea polyphenols in maintaining colour stability. This comparison highlights the broader potential of bio-based additives in optimising plant-dyed textiles for both durability and functional performance [22]. Similarly, Maulik et al. reported that Eucalyptus bark extract improved cellulosic and protein fibres' colour fastness and functional attributes through a simultaneous dyeing and functional finishing method. Their findings support using plant-based additives to enhance the durability and multi-functionality of dyed textiles, aligning with our approach of using tea polyphenols to improve dye stability and performance [23]. Tea polyphenols, with their abundant phenolic hydroxyl groups, interact with dye molecules to form stable complexes, thereby enhancing the adherence and bonding strength of the dyes on the fabric fibres. Additionally, the antioxidant properties of tea polyphenols help protect the dye molecules from degradation caused by external environmental factors (such as light exposure and oxidation), further enhancing the durability and stability of the dyes on the fabrics. Thus, tea polyphenols significantly improve the colour fastness of plant dyes through their unique chemical structure and biological activity. These findings are consistent with those of Zhang Yi et al., who reported that polyphenol-rich additives improve dye-fiber bonding, thereby mitigating fading and staining issues [12]. Additionally, comparisons with Onuegbu suggest that plant-derived antioxidants can be viable, eco-friendly alternatives to synthetic mordants commonly used in the textile industry [11].

The implications of these findings extend beyond textile dyeing. Plant dyes' enhanced stability and longevity suggest potential sustainable fashion applications, heritage textile preservation, and even biomedical fabric applications. Further studies should explore how these results compare with synthetic dyes regarding long-term wearability and exposure to environmental stressors such as humidity and pollutants [2,21].

In this study, six traditional plant dyes and three natural preservatives were systematically analysed through light and staining fastness tests. The experimental procedures included grinding plants, extracting dye solutions, and dyeing fabrics using traditional methods such as air-drying and re-dyeing. Different concentrations of natural preservatives were applied to enhance colour durability, and their effects on brocades made of various materials were compared.

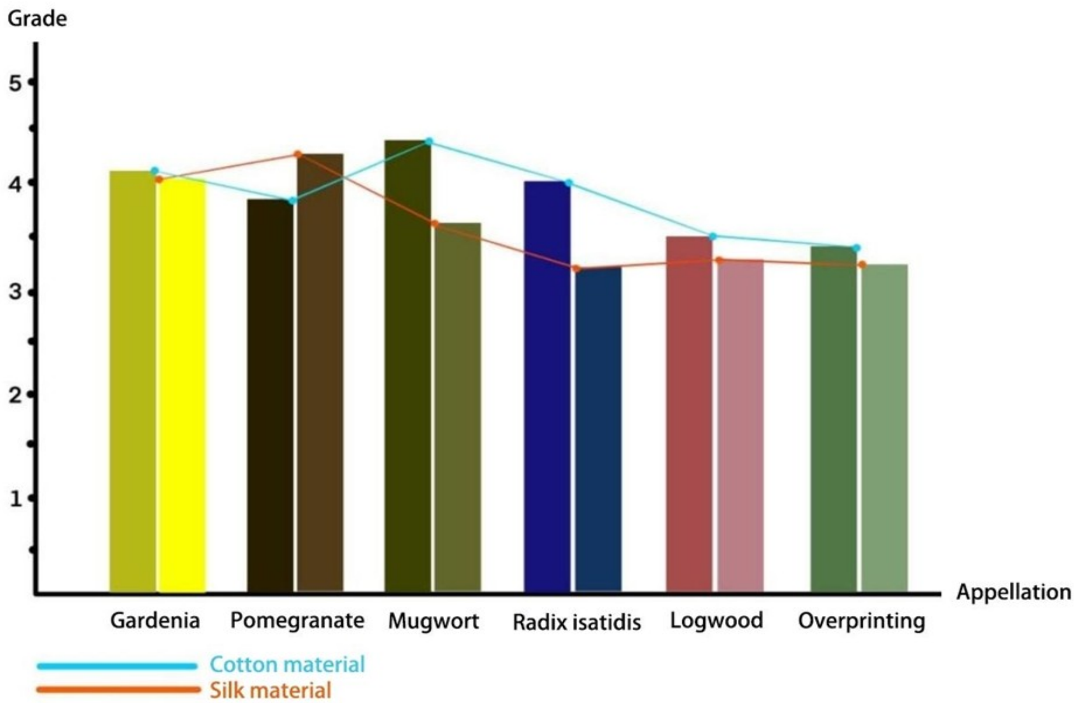


Figure 3. The final rating of staining fastness of different dyes in cotton and silk materials

The results demonstrated that tea polyphenols notably enhanced the colour fastness of Ai Grass and Pomegranate Peel dyes, as evidenced by improved performance in light and staining fastness tests [5,10]. As shown in Figure 3, the final staining fastness ratings for various dyes applied to cotton and silk materials underscored the efficacy of natural preservatives in improving colour stability [12]. These findings support the growing body of evidence suggesting that natural preservatives offer a promising solution to the challenges associated with plant dyeing, particularly in terms of enhancing the longevity and stability of colour. Moreover, comparisons with previous studies reinforce the notion that plant-based antioxidants can serve as sustainable stabilisers, reducing dependence on synthetic additives in textile dyeing [3,17,20].

CONCLUSION

This study advances the understanding of natural preservatives as sustainable enhancers for improving the colour fastness of plant-dyed textiles, offering novel contributions to the field of eco-friendly textile production. While prior research has explored the potential of plant dyes and natural additives individually, this work systematically bridges the gap between botanical preservative applications and textile durability, delivering actionable insights for academia and industry.

The key findings and their broader implications are summarised as follows:

1. Tea polyphenols emerged as a critical agent for enhancing lightfastness and washfastness in plant-dyed brocades. Their antioxidant properties significantly improved colour retention in Ai Grass (30% under washing) and Pomegranate Peel (50% under washing), demonstrating their potential to replace synthetic mordants. This aligns with global efforts to reduce reliance on toxic chemicals in textiles while addressing the persistent challenge of poor colour fastness in plant dyes.
2. The study highlights the interplay between fabric composition (e.g., silk vs. cotton) and dye-preservative efficacy. Silk exhibited superior compatibility with tea polyphenols, achieving up to 40% improvement in lightfastness, whereas cotton showed moderate gains. These findings emphasise the need for tailored preservation strategies based on fiber-dye interactions, advancing the optimisation of eco-friendly textile processes.
3. By validating the stability of plant dyes through natural preservatives, this research supports the scalability of sustainable textile practices. The improved durability of plant-dyed fabrics reduces resource waste and extends product lifespans, directly contributing to circular economy goals in the fashion and home textile sectors.
4. The successful integration of traditional dyeing techniques (e.g., Li brocade methods) with modern preservative science underscores the viability of preserving cultural heritage while meeting contemporary market demands. This dual focus on sustainability and cultural preservation positions plant-dyed textiles as competitive alternatives in global markets.

Future Directions:

While this study provides a foundational framework, further research should explore:

The long-term effects of natural preservatives under diverse environmental stressors (e.g., humidity, pollutants).
Scalable industrial protocols for preservative application, ensuring cost-effectiveness and consistency.
Broader ecological assessments, including lifecycle analyses of plant dye-preservative systems, validate their environmental benefits over conventional dyes.

Author Contributions

Conceptualisation, methodology, and formal analysis – Kong X, Fan J, Yang C; Investigation – Kong X, Fan J, Yang C; Resources – Yang C, Kong X, Fan J; Writing-original draft preparation – Kong X; Writing-review and editing – Yang C, Wang Y; Visualisation – Yang C; Supervision – Yang C. All authors had read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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