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Optimizing Lime Mordant Conditions for Cotton Dyeing with Dragon Fruit Peel Extract

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Abstract: This study investigates the extraction and application of natural colorants from dragon fruit (Hylocereus polyrhizus) peels for cotton fabric dyeing. A maceration process produced a concentrated anthocyanin-rich extract, with absorption peaks at 475 nm and 536 nm. Experiments were conducted using a completely randomized design with three replicates per treatment. The effects of lime (Citrus aurantifolia) mordant concentration, pH, and immersion time on dye uptake and retention were measured using UV-Vis spectrophotometry. Dye retention, calculated from absorbance differences before and after fabric immersion and post-wash, served as an indicator of color stability. Optimal retention was observed at 2% mordant concentration and pH 6.5, with absorbance-based dye retention values of 0.212 at 475 nm and 0.215 at 536 nm. Higher mordant concentrations and lower pH reduced dye stability and brightness, while immersion time significantly influenced retention, with peak values at 475 nm after 30 minutes and improved retention at 536 nm after 120 minutes. These results demonstrate the potential of dragon fruit peel extract as an eco-friendly textile dye and highlight the importance of optimizing mordant concentration, pH, and immersion time to achieve vibrant, durable colors.

Keywords: Dragon fruit peel; Immersion time; Mordant concentration; Natural dyes; Textile dyeing; UV-Vis spectrophotometry

Introduction

Natural dyes have received increasing attention as environmentally friendly alternatives to synthetic dyes, which are widely used in the textile industry but contribute significantly to water pollution and pose risks to human health (Ayele, Getachew, Kamaraj, & Suresh, 2021; Nambela, 2024; Sharma, 2024). Synthetic dyes are persistent, non-biodegradable, and often discharged into water bodies without adequate treatment, exacerbating ecological and health problems. In contrast, natural dyes are generally non-toxic, non-carcinogenic, and biodegradable, making them suitable for sustainable textile applications (Giovanazzi, 2024; Naidis, Lykidou, Mischopoulou, Vouvoudi, & Nikolaidis, 2023). The global demand for eco-friendly dyes has thus increased, driven by regulatory pressures and consumer preference for sustainable products.

Dragon fruit (*Hylocereus polyrhizus*) peel has emerged as a promising source of natural dyes due to its high anthocyanin content, which can produce vibrant red to purplish hues on cotton and silk fabrics (Bigambo, 2024; Mahmud, 2023). Several studies have demonstrated that plant-based materials, such as *Delonix regia* flowers, turmeric, olive peel, saffron, madder, and teak leaf extracts, can serve as effective natural dyes, highlighting the diversity of potential sources for eco-friendly textile applications (Almas, 2024; Mesrar, Tachallait, Cherkaoui, Bougrin, & Benhida, 2023; Naidis et al., 2023; Tibkawin, Suphrom, Nuengchamnong, Khorana, & Charoensit, 2021). Beyond textile coloring, natural dyes have applications in dye-sensitized solar cells, demonstrating their versatility and potential for sustainable technology development (Alim, Repon, Islam, Mishfa, Jalil, Aljabri, & Rahman, 2022). The use of agricultural and medicinal

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plant waste for dyeing not only reduces environmental impact but also adds value to by-products that would otherwise be discarded, aligning with circular economy principles and sustainable industry practices (Manyim, Kiprop, Mwasiagi, & Mecha, 2023).

Despite these advantages, a primary limitation of natural dyes is poor color fastness, which affects the longevity, brightness, and overall quality of dyed fabrics (Mesrar et al., 2023). Several strategies have been proposed to overcome this limitation, including the use of bio-mordants and controlled dyeing conditions. Lime (*Citrus aurantifolia*) has been identified as an effective bio-mordant that improves color retention, light fastness, wash fastness, and rub fastness in textiles, providing a non-toxic and environmentally sustainable alternative to traditional metal mordants (Benli, 2024; Ghaheh, Moghaddam, & Tehrani, 2021; Kusumastuti, Auliyana, & Rozana, 2023). The application of lime mordant facilitates stronger interactions between dye molecules and fiber surfaces, enhancing the stability and intensity of the resulting color.

Another critical factor influencing color fastness is immersion time during the dyeing process. Adequate immersion allows optimal dye penetration and fixation, preventing premature leaching and fading (Ihsan, Saputro, & Mahardiani, 2020). Previous research has shown that both the concentration of the mordant and the duration of immersion can significantly affect the quality and durability of dyed fabrics (Hosseinnezhad, Gharanjig, Razani, R, & Mr, 2021; Nateri & Dehnavi, 2021; Wahyuningsih, Kusumastuti, Krisnawati, Paramita, Yuniar, & Furi, 2022). Studies on various natural dyes, including jackfruit wood and pumpkin extracts, indicate that improper mordant application or suboptimal immersion times can lead to uneven coloration, reduced brightness, and lower fastness ratings, emphasizing the need for precise control of dyeing parameters.

UV-Vis spectrophotometry is widely used to quantify dye absorption and evaluate the interactions between natural dyes and mordants. By measuring absorbance at specific wavelengths, researchers can monitor dye uptake and retention on fabrics, providing a reliable indicator of color fastness (Pang, Arsad, Ahmadipour, Hamzah, Zaini, & Mohsin, 2022; Pratiwi, Rahmawaty, & Hasanah, 2022; Rivera-Hernández, Corona-Avendaño, Vázquez-Huerta, Palomar-Pardavé, Romero-Romo, & Ramírez-Silva, 2021; Tian, 2024). Such quantitative assessment allows for systematic optimization of dyeing conditions, including mordant concentration, pH, and immersion time, which is essential for achieving vibrant and durable colors.

Although several studies have explored the effects of mordants and immersion times on natural dyeing, there is a notable gap in the literature regarding the combined influence of lime mordant concentration and immersion time specifically for dragon fruit peel dye on cotton fabrics. Most research has focused on single-factor analyses or on other plant-based dyes, leaving uncertainty about the optimal conditions for maximizing color retention and stability in this context. Addressing this gap is crucial for improving the practical applicability of dragon fruit peel as a sustainable textile dye.

This study aims to systematically investigate the synergistic effects of lime mordant concentration and immersion time on dye absorption and retention using dragon fruit peel extract on cotton fabrics. Experiments were conducted using a completely randomized design with three replicates per treatment, and UV-Vis spectrophotometry was employed to quantify dye-mordant interactions. By determining the optimal dyeing conditions, this research provides practical insights for sustainable textile production and contributes to the broader understanding of eco-friendly dyeing strategies. The novelty of this work lies in its explicit evaluation of the interaction between mordant concentration and immersion time, which has not been previously examined in detail for dragon fruit peel dyeing on cotton, offering a framework for enhancing natural dye performance in industrial and educational applications.

Method

Materials

The materials used in this study included white cotton fabric pieces (10 × 20 cm), dragon fruit (*Hylocereus polyrhizus*) peel, lime (*Citrus aurantifolia*), methanol, distilled water, and detergent. Laboratory equipment consisted of a blender, analytical balance, spray bottle, sieve, knife, scissors, spatula, stirring rod, stopwatch, pH meter, rotary vacuum evaporator, UV-Vis spectrophotometer, volumetric flasks, measuring cylinders, beakers, Petri dishes, Erlenmeyer flasks, funnels, droppers, pipettes, test tubes, test tube racks, and standard laboratory glassware.

Sample Preparation

Dragon fruit peels were thoroughly cleaned to remove residual pulp and cut into small pieces. The pieces were blended into a fine pulp using a dry blender. The pulp underwent maceration with technical-grade methanol for 72 hours, refreshing the methanol every 24 hours. The extract was filtered, and the solvent was removed using a rotary vacuum evaporator to obtain a thick, concentrated dye extract. White cotton fabric pieces were pre-washed with detergent, rinsed thoroughly with distilled water, and air-dried.

Experimental Setup

Lime juice was extracted by washing, halving, and squeezing the limes. The juice was filtered and diluted with distilled water to prepare mordant solutions at five concentrations: 2%, 7%, 12%, 17%, and 22%. Pre-washed cotton fabrics were immersed in the respective mordant solutions for 24 hours and air-dried. Subsequently, the mordanted fabrics were immersed in a 10% dragon fruit peel extract solution for 60 minutes. After dyeing, the fabrics were rinsed with distilled water and air-dried.

The dye solution was diluted to 5 mL in a volumetric flask, and its absorbance was measured at the maximum absorption wavelengths (475 nm and 536 nm) using a UV-Vis spectrophotometer to determine dye uptake. Absorbance values before and after fabric immersion were recorded, and the fabrics were then rinsed in distilled water for 30 minutes to measure dye leaching. The absorbance of the rinse water served as an indicator of color fastness. The research workflow is illustrated in Figure 1.

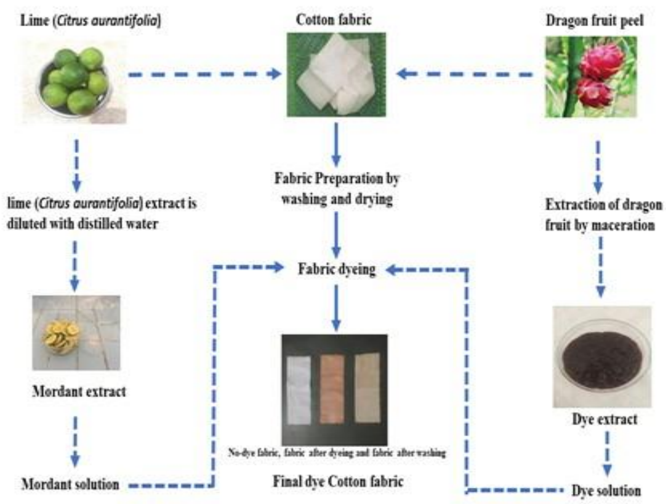

Figure 1. Research Flowchart

Parameters and Measurements

The primary parameter measured was color fastness, quantified using absorbance differences as follows:

Dye absorbed (Ax) = $A_1 - A_2$

Color fastness (Ay) = $Ax - A_3$

where:

A_1 = absorbance before fabric immersion

A_2 = absorbance after fabric immersion

A_3 = absorbance after washing

Higher differences in absorbance indicated better dye uptake, whereas lower absorbance in washing water reflected higher color fastness. All measurements were conducted in triplicate to ensure accuracy and reproducibility.

Experimental Design and Data Analysis

The study employed a completely randomized design (CRD) with three replicates per treatment. Data were analyzed using one-way ANOVA to evaluate the effects of mordant concentration, pH, and immersion time on dye uptake and retention. Post-hoc comparisons were conducted using Tukey's HSD test at a 5% significance level to determine significant differences between treatment groups. Statistical analyses were performed using Microsoft Excel and R software.

Result and Discussion

Extraction of Dragon Fruit Peel

Pigments were extracted from dragon fruit (Hylocereus polyrhizus) peel by maceration in methanol, yielding a dark, highly concentrated extract. UV-Vis spectrophotometry analysis revealed two prominent absorption peaks at 475 nm and 536 nm, corresponding to the initial anthocyanin detection and the maximum absorption of red pigments, respectively. The 475 nm peak is associated with the early presence of anthocyanins, while the 536 nm peak represents the characteristic absorption of betacyanins, confirming the presence of both pigment classes in the extract. The spectrum of the extract (Figure 2) closely aligns with previous studies (Khamidah, 2023; Handayani, 2023; Mahmud, 2023; Sari et al., 2018), validating the extraction method and demonstrating the purity of the pigments obtained.

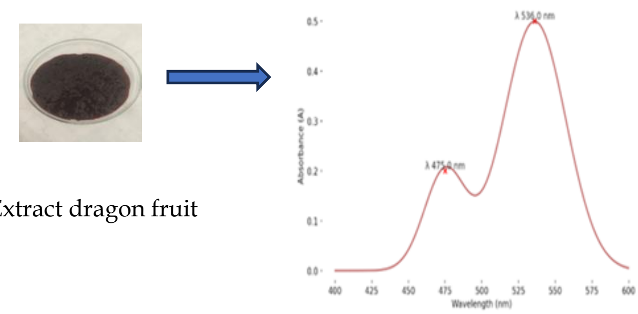

Figure 2. The spectrum of the maximum absorption wavelength

The concentrated extract was applied to cotton and silk fabrics, producing vibrant purplish-red hues. The extract's ability to achieve high color intensity without synthetic additives underscores its potential as an environmentally friendly alternative to conventional dyes. The results are consistent with previous research demonstrating that dragon fruit peel pigments can provide bright and stable coloration on textile substrates, with practical implications for sustainable dyeing in industrial and educational contexts (Mahmud, 2023; Sari et al., 2018).

Effect of Mordant Concentration on Dye Absorption and Fastness

The effect of mordant concentration on dye absorption and color fastness was analyzed at λmax 475 nm (see Table 1). At a 2% mordant concentration and pH 6.5, the dye's absorbance was 0.227, with a fastness of 0.212, indicating optimal dye retention and stability. This confirms that lower mordant concentrations provide the brightest and most stable colors on cotton fabrics.

At 7% mordant concentration, the absorbance decreased to 0.205, with an absorbance fastness of 0.173, indicating a slight reduction in color intensity and stability. At mordant concentrations of 12%, 17%, and 22%, the absorbance values were 0.179, 0.151, and 0.137, respectively, with corresponding absorbance fastness values of 0.134, 0.115, and 0.126. These trends are consistent with Kovačević et al. (2021) and Grande et al. (2023), who found that higher mordant concentrations lead to dye aggregation and reduced uniformity.

Table 1. Calculation results of fastness based on mordant at λ_{max} 475.0 nm

Mordant concentration	pH	Absorbance before soaking	Absorbance after soaking	Absorbance of absorbed dye	Absorbance after washing	Absorbance fastness
2%	6.5	1.866	1.629	0.227	0.035	0.212
7%	3	1.9	1.701	0.205	0.033	0.173
12%	2.8	1.888	1.696	0.185	0.017	0.134
17%	2.5	1.849	1.695	0.151	0.023	0.115
22%	2.5	1.815	1.67	0.156	0.027	0.126

Effect of pH on Dye Absorption and Fastness

pH was found to have a crucial role in dye absorption and fastness. As shown in Table 1, the optimal pH for maximum dye retention was 6.5, at which the highest absorbance fastness (0.215) was observed at 536 nm. At lower pH values, particularly for the 7% mordant concentration, the absorbance decreased to 0.197 and the absorbance fastness dropped to 0.183, indicating reduced color stability. This is in line with previous studies by Rosyida et al. (2021), who found that acidic conditions hinder the mordant-dye interactions, leading to poorer fixation and lower stability.

At lower pH levels (around 2.5–3), observed in the higher mordant concentrations (12%, 17%, and 22%), absorbance and fastness continued to decrease, confirming that overly acidic conditions reduce the efficiency of mordant application and the stability of the resulting dye. This highlights the importance of maintaining optimal pH conditions to ensure the effectiveness of natural dyes.

Impact of Mordant Concentration on Dye Absorption and Fastness at λmax 536.0 nm

Table 2 presents the color fastness results as a function of mordant concentration at λmax = 536.0 nm. The trend observed at 536 nm mirrors that at 475 nm, with lower mordant concentrations (2% and 7%) exhibiting higher absorbance fastness. At a 2% mordant concentration, the absorbance fastness was 0.215; at 7% mordant concentration, it was 0.183. However, as the mordant concentration increased, the absorbance and fastness values decreased, indicating oversaturation of the fabric fibers at higher mordant levels.

Table 2. Calculation results of fastness based on mordant at λ_{max} 536.0 nm

Mordant concentration	pH	Absorbance before soaking	Absorbance after soaking	Absorbance of absorbed dye	Absorbance after washing	Absorbance fastness
2%	6.5	1.843	1.639	0.201	0.037	0.215
7%	3	1.88	1.709	0.197	0.037	0.183
12%	2.8	1.891	1.687	0.179	0.028	0.138
17%	2.5	1.853	1.692	0.145	-0.004	0.122
22%	2.5	1.807	1.687	0.137	0.038	0.148

Tables 3. Calculation results of fastness based on immersion time at λ_{max} 475.0 nm

Immersion time (minutes)	Absorbance before soaking	Absorbance after soaking	Absorbance of absorbed dye	Absorbance after washing	Absorbance fastness
30	1.619116	1.312844	0.311266	0.007765	0.30372
60	1.691096	1.598701	0.093695	0.018656	0.08301
90	1.677893	1.563438	0.117078	0.016540	0.098872
120	1.676546	1.553507	0.114741	0.004297	0.10312

Impact of Immersion Time on Dye Fastness

The effect of immersion time on dye stability was analyzed at both λmax 475 nm (Table 3) and 536 nm (Table 4). Table 3 presents the results for λmax 475 nm. After 30 minutes of immersion, the absorbance fastness reached its maximum (0.30372), indicating that shorter immersion times are optimal for dye stability. However, as the immersion time increased to 60 minutes, absorbance fastness decreased to 0.08301, indicating that prolonged exposure led to some dye leaching. After 90 minutes, the absorbance fastness increased slightly to 0.098872, and at 120 minutes, it reached 0.10312. These results are consistent with the findings of Zhang et al. (2021), who reported that while initial immersion allows for rapid dye fixation, prolonged immersion may cause some dye leaching and reduce color stability.

At 536 nm, the absorbance fastness increased progressively with longer immersion times, with the highest value observed at 120 minutes (0.019084), as shown in Table 4. This suggests that extended immersion times improve the dye's stability at this wavelength, likely due to prolonged interaction between the betacyanins and the fabric fibers.

Tables 4. Calculation results of fastness based on immersion time at λ_{max} 536.0 nm

Immersion time (minutes)	Absorbance before soaking	Absorbance after soaking	Absorbance of absorbed dye	Absorbance after washing	Absorbance fastness
30	0.829430	0.826208	0.009404	0.009400	0.002760
60	0.848773	0.829603	0.016232	0.011850	0.007337
90	0.852179	0.831601	0.032286	0.014785	0.014250
120	0.834893	0.805251	0.036789	0.017530	0.019084

This study confirmed the findings of Kovačević et al. (2021) and Grande et al. (2023) regarding the mordant concentration, pH, and immersion time on dye absorption and fastness. However, this research provides new insights by evaluating the combined effects of these three parameters on the dyeing of dragon fruit peel extract. The findings suggest that lower mordant concentrations and neutral pH are optimal for achieving stable, bright colors. Furthermore, shorter immersion times lead to better dye stability, although longer immersion times improve fastness at 536 nm but may reduce fastness at 475 nm. These findings support the use of dragon fruit peel extract as a sustainable alternative to synthetic dyes in the textile industry. By optimizing the dyeing parameters, manufacturers can produce eco-friendly textiles that retain color vibrancy and stability over time.

The novelty of this study lies in its comprehensive evaluation of the interaction between mordant concentration, pH, and immersion time on dragon fruit peel extract dyeing. These findings provide valuable guidelines for textile manufacturers looking to adopt sustainable dyeing practices, enabling them to achieve vibrant, stable, and eco-friendly textiles. This research supports the growing interest in eco-conscious textile production, reducing reliance on synthetic dyes and harmful chemicals and contributing to a more sustainable textile industry.

Conclusion

This study successfully demonstrates that dragon fruit peel extract (*Hylocereus polyrhizus*) can be used as an effective natural dye for cotton fabric. The results indicate that mordant concentration, pH, and immersion time significantly influence dye absorption and color fastness.

A 2% mordant concentration at pH 6.5 provided the optimal color retention and stability, with an absorbance of 0.227 and an absorbance fastness of 0.212 at 475 nm. However, higher mordant concentrations (above 7%) reduced color intensity and stability, suggesting that moderate mordant concentration yields brighter, more stable colors.

pH played an important role, with neutral to slightly acidic conditions (pH 6.5) being the most favorable for maximum dye retention and fastness. Lower pH values (around 3) reduced color stability, especially at higher mordant concentrations. Additionally, immersion time significantly influences color stability. 30 minutes of immersion showed the best dye retention and stability at 475 nm (absorbance fastness of 0.30372). However, longer immersion times (e.g., 120 minutes) were shown to improve stability at 536 nm, reaching an absorbance fastness of 0.019084, although some dye leaching occurred.

This study also confirms that dragon fruit peel extract can serve as a sustainable and eco-friendly alternative to synthetic dyes. By optimizing dyeing conditions, such as mordant concentration, pH, and immersion time, manufacturers can produce fabrics with bright, stable, and eco-friendly colors.

The study provides valuable practical guidance for the textile industry to optimize natural dyeing processes. With careful control of these parameters, textile manufacturers can produce high-quality, vibrant, and durable textiles with minimal environmental impact, promoting a more sustainable textile industry.

Further research is needed to explore the application of dragon fruit peel extract on other types of fabrics and to evaluate the long-term durability of dyed fabrics under different environmental conditions.

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Author Contributions
Conceptualization: S., J., I., N.K.S., Y.C.M.; methodology: J., S., I., ; validation: N.K.J. and Y.C.M.; formal analysis: S., and N.K.J.; investigation: S.; resources: J. and I.; data curation: S. and N.K.J.; writing – original draft preparation: S. ; writing – review and editing: S., I., N.K.S; data visualization: S. and, J Y.C. M. All authors have read and agreed to the published version of the manuscript.

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The author states that there are no conflicts of interest regarding the research and its publication.

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