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EFFECTS OF PRE- AND POST-MORDANTING WITH DIFFERENT MORDANTS ON THE PRINTING OF WOOL FABRICS USING *RUBIA TINCTORUM* L. (MADDER)

RUBIA TINCTORUM L. (KÖKBOYA) KULLANILARAK YAPILAN YÜNLÜ KUMAŞLARIN BASKISINDA FARKLI MORDANLARLA ÖN VE SON MORDANLAMANIN ETKİLERİ

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ABSTRACT

This study examines the application of *Rubia tinctorum* L. (madder) as a natural dye in wool fabric printing, focusing on dyeing optimization and the effects of pre- and post-mordanting using various mordants. Wool fabrics were treated with iron(II) sulfate, alum, tannic acid, and tartaric acid before or after printing. For the printing process, the same mordants were used, with locust bean flour and gum arabic as thickeners. The impact of mordanting sequence (pre- vs. post-mordanting) on color yield and color fastness properties was analyzed to determine the optimal conditions for enhanced dye fixation and print quality. The results indicated that mordanting significantly enhanced color depth, with the highest color strength achieved through pre-mordanting with iron(II) sulfate. Natural mordants such as tannic and tartaric acids showed potential as effective alternatives to alum. Additionally, the color fastness to washing showed considerably high performance in terms of color change, although staining levels could be improved.

Keywords: Madder, natural dye, wool, anthraquinones, mordanting

ÖZET

Bu çalışmada, yünlü kumaş baskısında doğal boya olarak *Rubia tinctorum* L. (kök boya) uygulamasının, boyama optimizasyonunun ve çeşitli mordanlar kullanılarak yapılan ön ve son mordanlamanın etkileri üzerinde durulmuştur. Yünlü kumaşlar, baskıdan önce veya sonra demir(II) sülfat, şap, tannik asit ve tartarik asit ile işlem görmüştür. Baskı işlemi için, belirtilen mordanlar kıvamlaştırıcı olarak keçiboynuzu çekirdeği unu ve arap zamkı ile birlikte kullanılmıştır. Mordanlama sırasının (ön ve son mordanlama) renk verimi ve haslık özellikleri üzerindeki etkisi, geliştirilmiş boya fiksajı ve baskı kalitesi için en uygun koşulları belirlemek amacıyla analiz edilmiştir. Sonuçlar, mordanlamanın renk verimini önemli ölçüde artırdığını ve en yüksek renk veriminin demir(II) sülfat ile ön mordanlama yoluyla elde edildiğini göstermiştir. Tannik ve tartarik asitler gibi doğal mordanlar, şapa alternatif olabilecek potansiyele sahiptir. Ayrıca, yıkamaya karşı renk haslığı, renk değişimi açısından oldukça yüksek performans göstermiştir, ancak lekelenme konusunda geliştirmeye gerek duyulmaktadır.

Anahtar Kelimeler: Kökboya, doğal boya, yün, antrakinonlar, mordanlama

INTRODUCTION

Natural dyestuffs are colorants derived from plants, animals, or mineral sources, used to impart color to textile materials. These dyes are historically important for their use in textile and other industries. They are noted for their environmentally friendly and sustainable properties (Samanta & Agarwal, 2009). The use of natural dyes was shaped by the development of synthetic dyes, with early research focused on synthesizing dyes that mimic colorants found in nature (Lech et al., 2013; Pickering, 2005). Synthetic dyestuffs are becoming more suitable for industrial applications due to their various advantages, such as a wider color range, easy solubility and easy application, better color fastness properties, and higher stability against biodegradation (Ali et al., 2006; Gandhi & Shaikh, 2021; Harmon, 2020; Khattab & Rehan, 2018). In the mid-19th century, the discovery of synthetic dyestuffs reduced the importance of natural dyes; however, with the recent increase in demand for natural and sustainable products, natural-based dyestuffs have regained popularity (Başaran & Sarıkaya, 2015).

Natural dyestuffs minimize environmental impacts by being derived from renewable resources and reducing dependence on petrochemicals (Samanta & Agarwal, 2009; Andriamanantena et al., 2019). Since they are biodegradable, they cause less risk to human health and the environment compared to the harmful chemicals and byproducts contained in some synthetic dyes (Varjani et al., 2020; Mathur et al., 2006). The use of natural dyestuffs aligns with growing consumer demand for environmentally friendly and non-toxic products. They may be considered an alternative to sustainable textile dyeing practices. Additionally, natural dyestuffs can give textiles a unique and authentic look that cannot be easily achieved with synthetic dyes (Zhao & Liu, 2021; Kramell et al., 2019). Natural dyes, such as anthraquinones, especially in red, are widely preferred to provide bright colors in line with environmentally friendly dyeing methods (Varjani et al., 2020).

Rubia tinctorum L., commonly known as madder, is a perennial plant native to the Middle East and Mediterranean region (Sukenik et al., 2017). It has historically been important for textile dyeing, especially in the dyeing of wool, due to its rich anthraquinone content, which contains effective natural dyes such as alizarin, purpurin, and munjistin (Henderson et al., 2013; Deveoglu et al., 2012). It has been used for centuries as a source of red dye for wool dyeing (Ford et al., 2018). Research has focused on developing environmentally friendly processes for wool dyeing with madder, emphasizing cleaner and sustainable methods (Mehrparvar et al., 2016; Yusuf et al., 2016). Furthermore, its extract has been investigated for its potential to green-synthesize silver nanoparticles with anti-cancer features (Ghandehari et al., 2019).

Mordants are chemicals that improve the affinity, substantivity, and fastness properties of natural dyes by fixing them in or on a material through a reaction with the dye that creates an insoluble compound. They can be applied to textile materials before (pre-), during (simultaneous/meta-), or after dyeing (post-mordanting), where a chemical bond between the dye and fiber is necessary (Feiz & Norouzi, 2014; İşmal & Yıldırım, 2019). There are two main types of mordants: metallic mordants and bio-mordants. Metallic mordants, including Al^{3+}, Co^{2+}, Cr^{3+}, Cu^{2+}, Fe^{2+}, and Ni^{2+} based metal salts, offer strong bonding between dye molecules and fibers, resulting in high efficacy in dye fixation and color depth (Hosseinnezhad et al., 2022; Saxena & Raja, 2014; Zarkogianni et al., 2011). However, many of these mordants are unacceptable considering safety concerns, health, and environmental regulations. Among them, alum and iron are considered environmentally suitable substitutes for metal mordants; however, chromium is currently prohibited, copper is limited to low concentrations, and tin is undesirable in effluents (Saxena & Raja, 2014). On the other hand, bio-mordants including plant-derived tannins, crustacean-based chitosan, and plant oils such as sulphonated castor oil, are eco-friendly and biodegradable alternatives, posing less risk to the environment and human health (Hosseinnezhad et al., 2022; Repon et al., 2024; Saxena & Raja, 2014).

Madder is an effective dye source in wool dyeing due to its high anthraquinone content, which yields vibrant and long-lasting colors. Besides its application as a colorant, this natural dyestuff is gaining importance because of its versatility, as well as its pharmacological properties and antimicrobial activity. In the literature, various studies on protein-based textile materials dyed using *Rubia tinctorum* L. have been conducted. These studies focused on the use of madder for textile dyeing, especially in obtaining red tones (Deveoglu et al., 2012; Karadağ et al., 2014). In this study, madder was used as a natural dyestuff, and wool fabrics were mordanted with iron(II) sulfate, alum, tannic acid, and tartaric acid, and then printed with locust bean flour and gum arabic. The data obtained were evaluated, and color yield and color fastness properties were determined. To the best of our knowledge, there is no study on textile printing with *Rubia tinctorum* L. extract. Using both pre- and post-mordanting techniques, a distinctive material combination was applied in textile printing, involving: (1) two types of thickeners and their combinations, (2) four types of metallic- and bio-mordants, and (3) madder. In this context, our study aims to make an original contribution by filling this gap in the literature. The findings may contribute to sustainable textile printing practices by offering an alternative natural dye source and bio-mordant combinations.

MATERIALS AND METHODS

Materials

The ground *Rubia Tinctorum* L. used in this study was obtained from the Turkish Cultural Foundation (TCF), Cultural Heritage Preservation, and Natural Dyes Project Laboratory (DATU). The metal salts used for mordanting were tartaric acid: Merck Chemicals, iron(II) sulfate: Merck Chemicals, alum: ZAG Kimya, and tannic acid: Merck Chemicals. Locust bean flour (LBF), used as a thickening agent in printing paste, was purchased from Merck Chemicals, and gum Arabic (GA) was purchased from Smart Kimya. Acetic acid used for pH adjustment in dyeing and printing processes is of technical quality. ECE (A) non-phosphate detergent was used in the color fastness to washing test. The textile materials used in this study included 100% wool yarn for the dyeing processes and 100% wool 1×1 plain weave fabric for the printing processes. The properties of the fabric are listed in Table 1.

Table 1. Fabric Specifications

Composition	100% Wool	
Weave Type	Plain 1/1	
Yarn Count (Ne)	**Warp**	30
	Weft	30
Density (picks/cm)	**Warp**	30
	Weft	24
Mass per Unit Area (g/m^2)	143	

Methods

Preparation and Optimization of Madder Extracts

In the study, 10 g of the plant was added to 150 mL of distilled water to make a madder extract. Madder was extracted using a magnetic stirrer at 1000 rpm in an amber-colored, capped glass bottle under various conditions, with temperatures ranging from 30 to 95 °C and durations ranging from 15 to 90 minutes. The solution was then filtered using filter paper, and the extract was air-dried for use in dyeing. For printing, the extracts were used directly after filtration.

The dyeing process was carried out according to the dyeing graph shown in Figure 1, with a liquor-to-dye ratio of 1:20. The samples were dried at room temperature. The color strength (K/S) of the woolen fabrics after dyeing with the extracts obtained was measured with a Konica Minolta CM-3600d spectrophotometer. The most effective dyeing conditions were selected for printing processes.

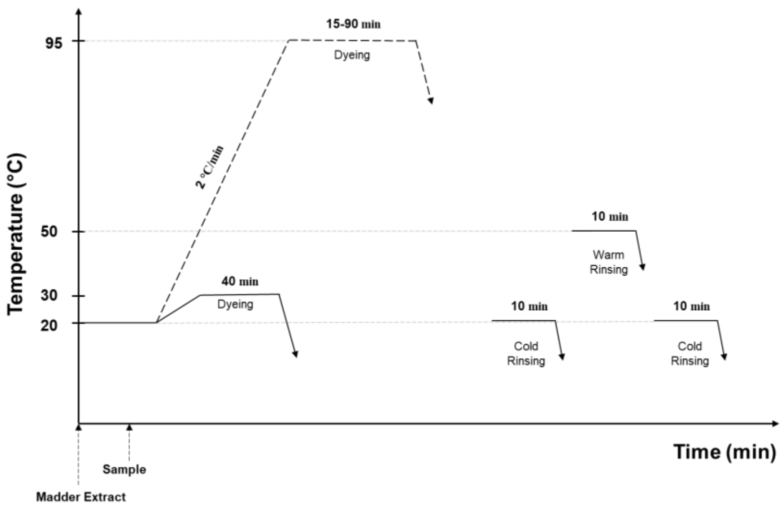

Figure 1. Dyeing Using Madder

Printing with Madder Extracts

Mordanting:

Tartaric acid, iron(II) sulfate, alum, and tannic acid were selected as mordants to increase the color yield and improve the color fastness properties in the dyeing of woolen products. In the printing process, both pre-mordanting and post-mordanting processes were applied to the woolen fabrics. The mordant concentration for the process was determined to be 3 g/L, liquor ratio of 1:20. The mordanting process was applied according to the graph shown in Figure 2. After mordanting, the samples were flat-dried at room temperature.

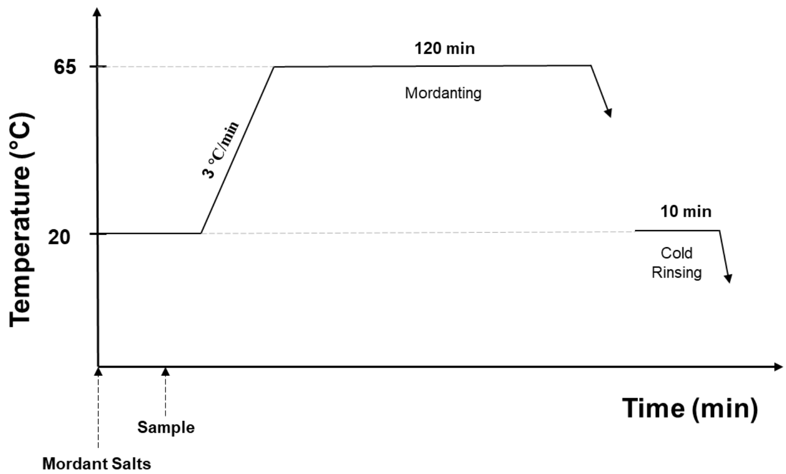

Figure 2. Mordanting Graph

Printing with Madder:

The printing process on woolen fabrics was carried out using the hand printing technique according to the recipes given in Table 2 using a 70-mesh screen. All of the printing pastes were filled to 1 kg with distilled water.

Table 2. Madder Printing Recipe

	CHEMICALS IN PRINTING PASTE			
Recipe	**Thickener**	**Thickener Amount**	**Madder Extraction**	**TOTAL**
R1	GA	110 g	200 mL	1000 g
R2	LBF	10 g	400 mL	1000 g
R3	GA:LBF 3:1 (w/w)	88 g	140 mL	1000 g
R4	GA:LBF 3:2 (w/w)	55 g	125 mL	1000 g

*The pH of the printing paste was adjusted to 5 with acetic acid.

The effect of different mordanting conditions on madder printability was evaluated using a Minolta Spectrophotometer CM-3600d (Konica Minolta, Tokyo, Japan) with CIELAB color system (D65 illuminant, 10° observer setting). In the CIELAB color system, color yield: K/S (Equation 1), a lightness coordinate scaled from 0 (black) to 100 (white): L*, the green-to-red measurement coordinate: a* and the blue-to-yellow measurement coordinate: b*, the distance from the colored point to the uncolored point, or saturation: C* (Equation 2) and hue: h° (Equation 3). R: % remission value, K: light absorption, and S: light reflectance.

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (1)$$

$$C^* = \sqrt{{a^*}^2 + {b^*}^2} \quad (2)$$

$$h = arctan\,(\frac{b^*}{a^*}) \tag{3}$$

The prints made with madder were examined for their color fastness to rubbing and washing. Color fastness to rubbing was performed using the TS EN ISO 105-X12:2016 standard. Color fastness to washing was tested under condition A1S of the TS EN ISO 105-C06:2010 standard, using ECE (A), non-phosphate detergent, and cotton fabric as the reference for staining.

RESULTS AND DISCUSSION

The colors of the wool fabrics printed with madder extract are generally light to dark shades of brownish orange with copper nuances. (Figure 3). When woolen fabrics were printed with madder extract without the use of mordant, it was observed that the fabrics showed good dyeability in light to medium darkness. Among the values obtained as a result of the measurements (Table 3), the highest color yield (K/S) was found to be at 95 °C and 45 minutes.

Table 3. K/S Value of Dyeing with Madder

Temperature (°C)	Time (min)	K/S Value
95	15	7,71
	30	9,02
	45	**9,46**
	60	8,01
	75	8,14
	90	8,69
30	**45**	5,37
45		7,83
60		7,11
75		8,61
90		8,95
95		**9,46**

Accordingly, four different printing recipes were prepared using two types of thickeners and their combinations, as seen in Table 2. Various mordanting methods were applied, including no mordant, pre-mordanting, and post-mordanting. In addition, various mordant chemicals were tested. Based on these applications, a comparative experimental design involving different thickeners, mordanting methods, and mordant types was developed. The individual effects of the mordanting method, formulation (recipe) differences, and mordant type on the color outcomes were evaluated and discussed separately, also considering color fastness results.

Impact of Thickener Type and Printing Recipe on Color Performance

Figure 3 visually presents wool fabric colors obtained from the experiments and calculated using tristimulus values based on CIE Lab color space coordinates with the 10° standard observer. The effect of thickener type and combinations on color performance was evaluated by considering color fastness results, taking into account three methods: pre-mordanting (Pre-M), no-mordanting (No-M), and post-mordanting (Post-M). Alum was used as the reference mordant during the discussion.

The main function of thickeners, which are important for textile printing processes, is to preserve dyestuff and other auxiliary agents in an inert medium to avoid unfavorable chemical reactions. The rheological characteristics of thickeners in the printing pastes are correlated with the soil (dry matter) content (Saad et al., 2022). In the present case, blends of low-viscosity GA, which has a high soil content, and high-viscosity LBF, which has a low soil content, were employed. It is possible that increased viscosity resulting from a higher dry matter content may impact dye migration and adhesion, potentially enhancing color yield. It is known that high soil-content pastes, such as GA, exhibit higher resistance to dye uptake by hydrophilic fibers, like wool. Therefore, it makes dye diffusion more difficult, whereas low-soil-content pastes such as LBF enable complete dye transfer to fabric when sufficient viscosity is achieved (Yurdakul & Atav, 2016). The order of increasing soil content was R1 (100% GA) >R3 (GA:LBF 3:1) >R4 (GA:LBF 3:2) >R2 (100% LBF).

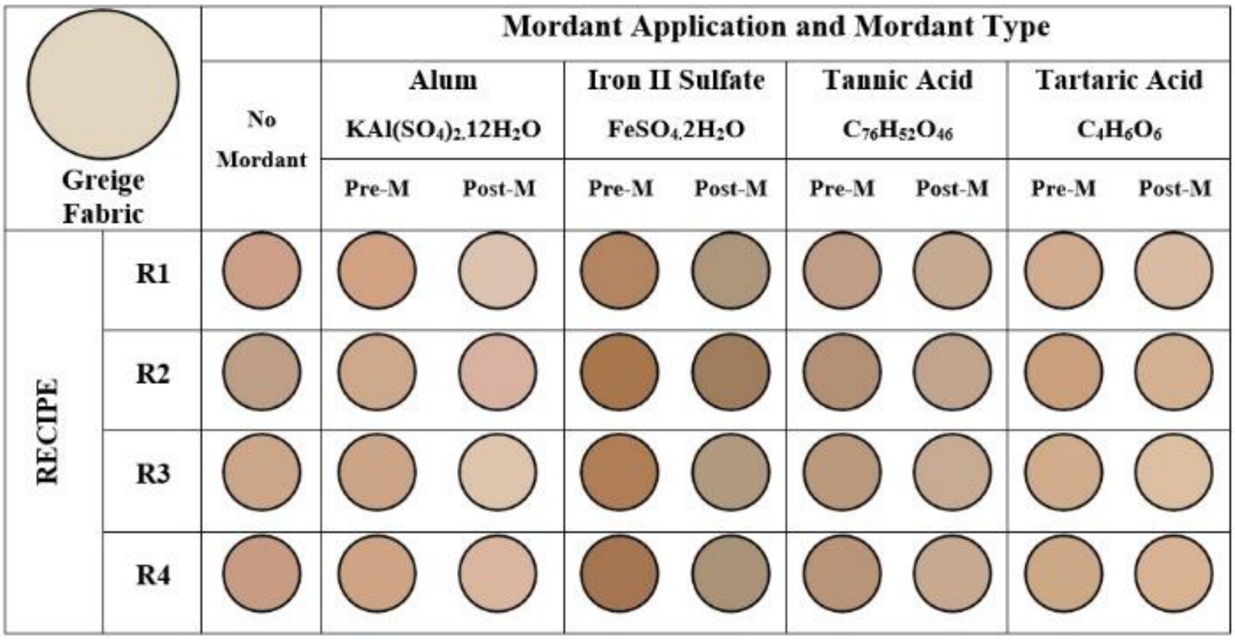

Figure 3. Visual Demonstration of Wool Fabric Colors; (R1: Recipe 1, R2: Recipe 2, R3: Recipe 3, R4: Recipe 4, Pre-M: Pre-Mordanting, Post-M: Post-Mordanting)

Table 4. Colorimetric Data of Madder-Printed Wool Fabrics Using Alum Mordant

Recipe	Method	Colorimetric Values					
ALUM		L*	a*	b*	C*	H°	K/S
1	**Pre-M**	**70.30**	**13.21**	**22.14**	**25.78**	**59.18**	**1.63**
	No-M	69.80	12.79	18.87	22.80	55.86	1.49
	Post-M	80.54	6.27	13.44	14.83	64.99	0.60
2	**Pre-M**	**72.04**	**9.72**	**20.15**	**22.37**	**64.25**	**1.38**
	No-M	67.80	9.22	16.03	18.49	60.08	1.46
	Post-M	75.43	11.79	13.81	18.16	49.52	0.76
3	**Pre-M**	**71.04**	**10.09**	**21.41**	**23.67**	**64.78**	**1.68**
	No-M	71.30	9.90	20.17	22.47	63.85	1.53
	Post-M	80.75	6.27	14.50	15.80	66.63	0.64
4	**Pre-M**	**70.68**	**11.42**	**22.48**	**25.21**	**63.08**	**1.73**
	No-M	68.14	12.07	19.91	23.28	58.77	1.77
	Post-M	76.70	10.13	16.05	18.98	57.76	0.82

The order of the color yield was calculated as follows: R4 (GA:LBF 3:2) > R3 (GA:LBF 3:1) > R1 (100% GA) > R2 (100% LBF) (Table 4). The best color yield was observed in GA:LBF blends, which may be attributed to their moderate dry matter content and balanced viscosity, combining GA's adhesion benefits with LBF's enhanced dye diffusion properties. R1 yielded a moderate color, although GA has low viscosity; its high solid content may have restricted dye penetration into the wool fibers. In contrast, R2 resulted in the lowest color yield. Despite low dry matter, its naturally high viscosity likely created a barrier for dye diffusion. Its naturally high viscosity probably acted as a barrier to dye diffusion despite the low solid content. The color change after washing showed a high color fastness rating (5), indicating no noticeable color change regardless of the presence or method of mordanting (Table 5).

Impact of Mordanting Methods on Color Performance

As previously indicated, recipes with madder extract were printed in three different mordanting conditions: without mordanting, with pre-mordanting, and with post-mordanting. Alum was selected as the reference mordant for comparison. As evidenced by the findings, even without mordanting, a visible coloration was obtained by madder-printing on wool. Pre-mordanting resulted in a higher color yield (K/S) compared to post-mordanting or no mordanting. In contrast, post-mordanting gave the lowest K/S value, likely because the dyeing had already occurred and the mordant–dye interaction negatively affected color development (Table 4). Compared to the control (No-M), both pre-mordanted and post-mordanted fabrics exhibited increased lightness (L*), indicating a brighter appearance. Feiz and Norouizi (2015) studied the effect of various mordants, including alum and ferrous sulfate, on wool dyeing with madder. For alum, the pre-mordanting procedure yielded a higher color strength, which aligns with our findings (Feiz & Norouzi, 2015).

However, the color fastness results showed higher grades in post-mordanted fabrics, indicating more durable coloration in terms of both rubbing and staining after washing. Although both pre- and post-mordanted samples showed a high washing fastness rating (5), the post-mordanted fabric exhibited less staining (4, 4/5, and 5), accompanied by a lower color yield (K/S), whereas the pre- and non-mordanted samples showed a staining grade of 1. This may be attributed to partial removal of unfixed or weakly bound surface dyes during the post-mordanting bath or to the formation of stronger dye-fiber interactions that limit dye transfer (Table 5).

Table 5. Color Fastness Results of Madder-Printed Wool Fabrics Using Alum Mordant

Recipe	Method	Fastness Results			
		Rubbing Fastness		Washing Fastness	
ALUM		Dry	Wet	Color Change	Staining
1	**Pre-M**	**2**	**3/4**	**5**	**1**
	No-M	2/3	2/3	5	1
	Post-M	5	4	5	5
2	**Pre-M**	**4**	**3/4**	**5**	**1/2**
	No-M	3/4	4/5	5	1/2
	Post-M	4/5	3	5	4/5
3	**Pre-M**	**2**	**3/4**	**5**	**1**
	No-M	2/3	4	5	1
	Post-M	4/5	4	5	4/5
4	**Pre-M**	**2/3**	**2**	**5**	**1**
	No-M	2/3	3/4	5	1
	Post-M	4/5	4	5	4

Impact of Different Mordant Types on Color Performance

Since the pre-mordanting process produced a darker tone compared to other methods, it was selected for the subsequent stages, particularly for investigating the effect of mordant type on dyeing depth. As presented in Table 6, when the effects of different mordants on dyeing woolen fabrics with madder were evaluated, it was observed that the use of iron(II) sulfate resulted in darker colors (higher K/S values) than the other mordants. The use of iron salts is known to substantially affect the resulting colors, producing darker shades, and was employed in early textile dyeing to improve color yield (Feiz & Norouzi, 2015; Manhita et al., 2011).

Additionally, there was a notable shift in color towards red (+a*) and yellow (+b*) coordinates, while the lightness value (L*) decreased comparatively. On the other hand, although relatively higher lightness values were obtained when using alum and tartaric acid as mordants, the color yield was found to be lower.

Shams Nateri and Dehnavi (2022) studied dyeing with madder using alum as a mordant and reported that pre-mordanting resulted in higher lightness values compared to post-mordanting, which contrasts with our findings. In their study, the b* values for pre-mordanted samples were approximately 20, while a* values ranged between 10 and 20 depending on the mordant concentration. Nevertheless, a similar hue angle (h°) was obtained, ranging between 60 and 65. In another study by Manhita et al. (2011), wool fibers were mordanted for madder dyeing. It was found that fibers dyed with an alum mordant exhibited higher L* values compared to those treated with iron, which is consistent with our findings.

Organic mordants used in this study (tannic acid and tartaric acid) resulted in a similar color yield to alum, which is an inorganic metal salt. Tannic acid has a light-yellowish color, which may help enhance the final color. In contrast, tartaric acid is white, which might explain its lower K/S value compared to tannic acid. Considering the ecological impacts of pollution, the discharge of inorganic metal salts requires additional treatment, such as precipitation or filtration, to clean the wastewater (Rather et al., 2016). Therefore, bio-mordanting can be considered as an alternative method of mordanting compared to alum in wool printing.

Table 6. Colorimetric Data of Madder-Printed Wool Fabrics with Pre-Mordanting Using Various Mordants

Recipe	Method	Colorimetric Values					
	Pre Mordant	**L***	**a***	**b***	**C***	**H°**	**K/S**
1	**Alum**	70.30	13.21	22.14	25.78	59.18	1.63
	Iron(II) Sulphate	**59.26**	**14.03**	**25.87**	**29.43**	**61.53**	**3.77**
	Tannic Acid	67.69	9.10	17.03	19.31	61.90	1.87
	Tartaric Acid	72.92	9.27	20.20	22.23	65.34	1.26
2	**Alum**	72.04	9.72	20.15	22.37	64.25	1.38
	Iron(II) Sulphate	**54.31**	**14.57**	**30.45**	**33.75**	**64.44**	**7.32**
	Tannic Acid	62.33	9.79	19.02	21.39	62.77	2.91
	Tartaric Acid	68.92	11.16	23.42	25.95	64.52	1.70
3	**Alum**	71.04	10.09	21.41	23.67	64.78	1.68
	Iron(II) Sulphate	**57.19**	**15.01**	**29.29**	**32.91**	**62.86**	**5.24**
	Tannic Acid	65.58	8.87	19.83	21.72	65.90	2.60
	Tartaric Acid	73.17	8.57	21.32	22.98	68.09	1.45
4	**Alum**	70.68	11.42	22.48	25.21	63.08	1.73
	Iron(II) Sulphate	**53.57**	**14.93**	**27.68**	**31.46**	**53.66**	**6.63**
	Tannic Acid	64.56	10.46	19.66	22.27	61.98	2.57
	Tartaric Acid	71.62	8.61	22.15	23.76	68.76	1.59

Table 7. Color Fastness of Madder-Printed Wool Fabrics with Pre-Mordanting Using Various Mordants

Recipe	Method	Fastness Results			
		Rubbing Fastness		Washing Fastness	
	Pre Mordant	**Dry**	**Wet**	**Color Change**	**Staining**
1	**Alum**	2	3/4	5	1
	Iron(II) Sulphate	**2**	**3/4**	**4/5**	**1**
	Tannic Acid	3	3/4	5	3
	Tartaric Acid	3/4	3/4	5	1
2	**Alum**	4	3/4	5	1/2
	Iron(II) Sulphate	**2/3**	**4**	**5**	**4**
	Tannic Acid	3/4	3/4	5	3
	Tartaric Acid	4	4/5	5	2/3
3	**Alum**	2	3/4	5	1
	Iron(II) Sulphate	**2**	**4**	**5**	**1**
	Tannic Acid	3/4	4	5	1
	Tartaric Acid	3	3	5	1
4	**Alum**	2/3	2	5	1
	Iron(II) Sulphate	**1/2**	**3**	**5**	**1**
	Tannic Acid	2/3	4/5	5	1
	Tartaric Acid	2/3	4	5	1/2

The color fastness results of madder-printed wool fabrics treated with different mordants with the pre-mordanting technique are given in Table 7. It is observed that madder-printed fabrics exhibit good color fastness to washing in terms of color change and moderate color fastness to rubbing. However, the fabrics exhibited a high level of staining during washing process. To address this issue, an additional after-treatment process may be applied to improve the color fastness properties. This treatment has a low potential to affect color strength, as evidenced by the excellent color fastness values observed in terms of color change.

CONCLUSIONS

This study examined the printing ability of wool fabric with madder (*Rubia tinctorum* L.) using two different thickeners: locust bean flour, gum arabic, and their combinations, as well as various mordants, including organic acids (tannic acid and tartaric acid) and inorganic metal salts (alum and iron(II) sulfate). The effects of different mordanting techniques (pre- and post-mordanting) were also discussed. To the best of our knowledge, no study has yet reported this specific combination or approach in the literature. The color of the wool fabric primarily depends on the characteristics of the mordant, the mordanting technique, and the type of printing paste. The colorimetric analysis revealed that the lightness (L*), chroma (C*), and hue angle (h°) were altered with changes in the mordanting technique and mordant types. This is probably because different fiber-mordant-chromophore complexes are formed under different dyeing conditions. It can be concluded that the alum, an inorganic metal salt, yielded a similar color to natural mordants (tannic acid and tartaric acid), while iron(II) sulphate produced the highest color yield of all. Therefore, natural mordants can be considered an effective and environmentally friendly alternative to alum in terms of printing of natural dyestuffs. A general assessment of fastness properties revealed high performance in terms of color change for color fastness to washing. Although rubbing fastness was commercially acceptable, staining levels suggested a need for improvement. Consequently, a subsequent treatment process may be proposed.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Artificial Intelligence Contribution Statement

This article was written, edited, analyzed, and prepared entirely by the authors without the assistance of any artificial intelligence tools. AI was only used to enhance the clarity of the manuscript's language. No other part of the content, including data analysis or figures, was generated or modified by AI.

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