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Impact of Natural Dyes Cochineal (Dactylopius coccus) and airampo (Opuntia soehrensii) on the Physico-Mechanical Properties and Colorfastness of Alpaca (Vicugna pacos) Yarns

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ABSTRACT

The effect of dyeing with natural colorants on the physico-mechanical properties, colorimetric parameters, hydrophobicity, and color fastness of alpaca threads (Vicugna pacos) was investigated. Two dyes from the Andes were evaluated: cochineal (Dactylopius coccus) and airampo (Opuntia soehrensii), using a post-mordanting method with sodium sulfate (Na_2SO_4), oxalic acid ($C_2H_2O_4$), and potassium alum ($KAl(SO_4)_2{\cdot}12\,H_2O$). The analysis of the results showed that the dyeing treatments did not significantly affect the elongation (51–65%), maximum strength (1.64–1.94 N), or tenacity (0.93–1.10 MPa) of the threads. Regarding colorimetry, cochineal produced intense red shades (a* = 34.95) and the highest saturation (C*) of up to 40.29. Meanwhile, airampo generated warm, bright yellow tones (L*) up to 70.19. A critical finding was the low wash fastness, with ratings of 1 to 2 on the grayscale. However, the rub fastness ranged from moderate to good (2 to 4–5). Dyeing with pure cochineal increased the hydrophobicity of the thread, reaching a contact angle of 97.22°. These results indicate that, although the dyes offer a rich color range without compromising the fiber, it is essential to optimize the process to improve color fixation before commercialization.

摘要

本研究探讨了天然染料染色对羊驼毛线 (Vicugna pacos)物理机械性能、色度参数、疏水性及耐色牢度的影响. 对安第斯山脉的两种染料——胭脂虫红 (Dactylopius coccus)和阿伊安波红 (Opuntia soehrensii)进行了评估，采用硫酸钠 (Na2SO4)、草酸(C2H2O4)和明矾 (KAl(SO4)2·12H2O)进行后媒染处理. 结果分析表明，染色处理对纱线的伸长率 (51%-65%)、最大强度 (1.64-1.94 N)和断裂强力 (0.93-1.10 MPa)均无显著影响. 在比色学方面，胭脂虫染料呈现出浓烈的红色调 (a* = 34.95)和高达40.29的最高饱和度 (C*)。同时，安纳托米黄产生了温暖明亮的黄色调 (L*)，亮度值可达70.19. 一个关键的发现是洗涤牢度低，灰度等级为1至2。然而，摩擦牢度从中等到良好 (2到4-5)不等。用纯胭脂红染色增加了线的疏水性，接触角达到97.22°. 这些结果表明，尽管染料在不损害纤维的情况下提供了丰富的颜色范围，但在商业化之前，优化工艺以提高固色性至关重要.

KEYWORDS

Vicugna pacos; sustainable dyeing; cochineal; airampo; color fastness; mechanical properties

关键词

维库纳.帕科斯; 可持续染色; 胭脂虫醛; 色牢度; 力学性能

Introduction

The global textile industry is undergoing a significant shift toward sustainability, driven by stricter environmental laws and a growing social awareness of the ecological impacts of industrial production (Abbate et al. 2023). This change addresses the urgent need to reduce the water and carbon footprint of a sector traditionally associated with high resource use and the production of solid waste and pollutants.

In this case, natural fibers serve as effective alternatives to synthetic materials due to their biodegradability, lower environmental impact, and compatibility with low-energy processes (Rahaman and Pranta

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2024). Among these, alpaca fiber (Vicugna pacos), native to the high Andean regions, is notable for its exceptional softness, fineness, shine, and thermal insulation properties (Díaz-Garay, Larios-Francia, and Gorritti 2021).

In addition to its technical properties, alpaca fiber holds significant sociocultural value, as its production strengthens the economic development of vulnerable rural communities, preserves ancestral spinning and weaving practices, and contributes to the conservation of Andean cultural heritage (Balladares Zevallos 2024; Liberman 2021). Compared to other animal fibers, this fiber exhibits greater elasticity, making it a preferred choice for the production of luxury textiles and high-comfort garments (Jankowska et al. 2021).

The evaluation of dyeing effects on textile materials requires a thorough analysis that includes both physico-mechanical parameters and colorfastness indicators. Among these, elongation at break, maximum force, and toughness are key for assessing the yarn's structural strength (Jankowska et al. 2021). Similarly, hydrophobicity is a crucial property, as it influences how fibers interact with water and respond to environmental humidity (Naebe et al. 2010).

Regarding color characterization, the CIELAB system allows a quantitative description of the optical properties of materials through the parameters L*, a*, b*, C*, and h°, which represent luminosity, chromaticity, saturation, and hue, respectively (Lindon, Holmes, and Tranter 2019). The color fastness, assessed through washing and rubbing tests, is a key indicator of color durability.

Our study sets itself apart from previous research by adopting a comprehensive and multidimensional approach that significantly expands the methodological scope. Unlike Lozano, Quispe-Quispe, and Vilcanqui-Pérez (2024), who focused solely on how mordants affect the diameter and color tone of alpaca threads dyed with collie flowers (Buddleja coriácea), our research includes natural dyes from both plant and animal sources (airampo and cochineal). It also evaluates their colorimetric, physical-mechanical, and hydrophobic properties simultaneously. This approach enables us to investigate how the type of mordant affects fiber structure, a factor that Lozano did not consider. Furthermore, unlike Palacios-Ochoa, Guillén Serrano, and Siddons (2021), who only analyzed the colorfastness of wool and alpaca fabrics without addressing mechanical performance or water resistance, our study provides a comprehensive characterization of the colorfastness, tenacity, and water repellency of alpaca threads, offering a more complete assessment of the dyed material's performance.

Contemporary research has moved beyond the ethnographic approach, which focused on preserving ancestral techniques, to view natural dyeing as a field of scientific innovation centered on efficiency and reproducibility (Yadav et al. 2025; Adeel et al. 2019). New technologies, such as microwave assistance, sonochemical ultrasound, and plasma surface modification, have shown improvements in dye affinity and reductions in energy use (Eyupoglu et al. 2024; Gotoh 2020; Sankhasti, Barani, and Khazaei 2025).

Recent studies indicate that biomordants, such as pomegranate extracts, soy proteins, and tannic acid, can match or even outperform metallic mordants in terms of colorfastness on fibers like wool and mohair. Moreover, these compounds offer additional functional properties, including antibacterial activity (C. Eyupoglu, Eyupoglu, and Merdan 2022; Periyasamy 2022; Tegegne et al. 2024).

Alpaca thread is produced by twisting its fibers, a process that can be performed manually or mechanically, and directly affects properties such as thickness, uniformity, and strength (Díaz-Garay, Larios-Francia, and Gorritti 2021). Dyeing, which involves chemical reactions between the fiber, mordant, and dye, can change the thread's structural integrity, impacting its tenacity, elasticity, and moisture behavior (Rahman et al. 2025). Therefore, selecting the appropriate dyeing methods and conditions is crucial for maintaining the quality of the final product.

In a context of growing demand for sustainable textiles that also emphasize cultural heritage, alpaca fiber is seen as an ideal material (Ortiz 2023). However, to ensure its competitiveness in international markets, it is crucial that dyeing with natural dyes does not compromise its physico-mechanical properties or its color stability (Arnob Dhar Pranta 2024; Jankowska et al. 2021; Palacios-Ochoa, Guillén Serrano, and Siddons 2021).

The scientific literature reveals a gap in studies that simultaneously examine mechanical, colorimetric, durability, and hydrophobicity parameters in alpaca fiber. Although some investigations have explored colorimetry and durability, a comprehensive characterization is still needed to correlate these factors with the material's durability and functional performance.

The objective of this research was to evaluate the impact of natural dyes from cochineal and airampo, in the presence of mordants, on the physical-mechanical and colorfastness properties of alpaca yarn. The novelty of the study lies in its comprehensive characterization, which combines the analysis of mechanical properties, colorimetry, colorfastness, and hydrophobicity in a single study, thereby filling a gap in the existing literature. The contribution of this work is to provide solid scientific data for optimizing the dyeing process of alpaca fiber, promoting the sustainable use of native resources, and adding value to the local production chain.

Materials and methods

Materials

The study used 100% natural alpaca yarn, with a count of 10.5/3 Nm, Z-twist, presented on cones, supplied by the company Michel y Cía. S.A., located in Cusco, Peru. The mordants used were of technical grade and purchased from a specialized textile supplies store in Cusco. These included sodium sulfate (Na_2SO_4), locally known as "collpa"; aluminum and potassium dodecahydrate sulfate ($KAl(SO_4)_2{\cdot}12\,H_2O$), called "alum"; and oxalic acid ($C_2H_2O_4$), commonly referred to as "lemon salt." For natural dyes, powdered cochineal (Dactylopius coccus), obtained from the same commercial source in Cusco, and prickly pear fruit (Opuntia soehrensii), locally collected in the city of Abancay, Apurímac region, were used as dye sources.

Extraction of dyes

To extract dye from cochineal (Dactylopius coccus), a 0.08% (w/v) solution was prepared by dissolving 800 mg of cochineal powder in 1000 mL of distilled water. The mixture was heated to 92°C with constant stirring for 2 hours. These conditions were chosen to maximize carminic acid extraction and prevent its heat degradation. Then, the extract was filtered to remove solid residues, resulting in a clear extract (Arroyo Figueroa et al. 2021).

The dye extraction from airampo (Opuntia soehrensii) was performed using 90 g of dehydrated pulp in 3000 mL of distilled water. The mixture underwent solid–liquid extraction at a boiling point of 92°C for 30 minutes. Unlike cochineal, gentle conditions were maintained to prevent the degradation of betacyanins, especially betanin, which are sensitive to heat. Finally, the dye was separated from the leftover seeds using sterile gauze.

Characterization of dye extracts and mordants

The chemical analysis of the dye extracts, mordants, and alpaca fiber was performed using Fourier Transform Infrared Spectroscopy (FTIR). This technique was used to identify the main functional groups in the cochineal (Dactylopius coccus) and prickly pear (Opuntia soehrensii) extracts, as well as in the mordants: sodium sulfate (Na_2SO_4), aluminum sulfate, potassium dodecahydrate ($KAl(SO_4)_2{\cdot}12\,H_2O$), and oxalic acid ($C_2H_2O_4$). The spectra were recorded with an FTIR spectrophotometer (Thermo NICOLET iS50, Waltham, MA, USA) over a range of 400–4000 cm^{-1}. To ensure data quality and consistency, each final spectrum was obtained by averaging 64 scans.

Dyeing process

According to Table 1, the dyeing process was carried out using the post-mordanting technique to enhance color fixation and produce a variety of shades on 10 g of alpaca threads. Nine treatments were established: one control (T_0, without dyeing or mordanting) and eight experimental treatments (T_1–T_8), distinguished by the type of dye and mordant used. Treatments T_1 to T_4 used cochineal (6 g) as the dye, with variations in mordant: alum (T_2), lemon salt (T_3), collpa (T_4), and no mordant (T_1). Treatments T_5 to T_8 used airampo (22.5 g), applying the same mordants as T_6 (alum), T_7 (lemon salt), T_8 (collpa), and no mordant in T_5. Each sample was boiled for 30 minutes in the respective dye extract, then 1 g of mordant was added according to the treatment, followed by an additional 5-minute boil at 92°C to ensure fixation. Finally, the threads were rinsed with nonionic water and dried at room temperature, following the protocol adapted from Samanta and Konar (2011).

Table 1. Treatments with natural dyes and mordants for thread dyeing.

Treatments	Name
T_0	Alpaca yarn
T_1	Alpaca yarn10 g + cochineal 6 g
T_2	Alpaca yarn 10 g + cochineal 6 g + alum ($KAl(SO_4)_2{\cdot}12H_2O$) 1 g
T_3	Alpaca yarn 10 g + cochineal 6 g + citric acid ($C_2H_2O_4$) 1 g
T_4	Alpaca yarn 10 g + cochinel 6 g + collpa (Na_2SO_4) 1 g
T_5	Alpaca yarn 10 g + airampo
T_6	Alpaca yarn 10 g + airampo 22.5 g + alum ($KAl(SO_4)_2{\cdot}12H_2O$) 1 g
T_7	Alpaca yarn 10g + airampo 22.5 g + citric acid ($C_2H_2O_4$) 1 g
T_8	Alpaca yarn 10 g + airampo 22.5 g + collpa (Na_2SO_4) 1 g

$KAl(SO_4)_2{\cdot}12H_2O$, aluminum potassium sulfate dodecahydrate; $C_2H_2O_4$, oxalic acid; Na_2SO_4, sodium sulfate.

Evaluation of physico-mechanical properties

According to Figure 1, the mechanical characterization of the threads was performed through tensile tests following the guidelines of ASTM standard D2256 (ASTM International 2022). A RapidTA Max texture analyzer (Stable Micro Systems, Surrey, United Kingdom) was used, operated at a constant speed of 20 mm/min. During the tests, key mechanical parameters, including maximum force (N), elongation at break (%), toughness, and Young's modulus (MPa), were recorded, enabling the assessment of the samples' strength and elasticity under controlled conditions.

The elongation at break (ε_r), which indicates the percentage of elongation of the thread until the breaking point, was calculated using Equation (1); by measuring the initial and final lengths of the thread.

$$\varepsilon_{r=}\left(\frac{L_f - L_0}{L_0}\right) \times 100 \tag{1}$$

where: L_0 is the initial length of the thread and L_f is the final length at the moment of breakage.

The maximum force, denoted as F_{max}, corresponding to the highest load value recorded before the thread's rupture, was determined during the tensile test as an indicator of the material's mechanical strength.

Tenacity (T), which indicates the thread's resistance to tensile stress, was calculated as the ratio of the maximum applied force to the initial cross-sectional area of the thread, according to Equation (2):

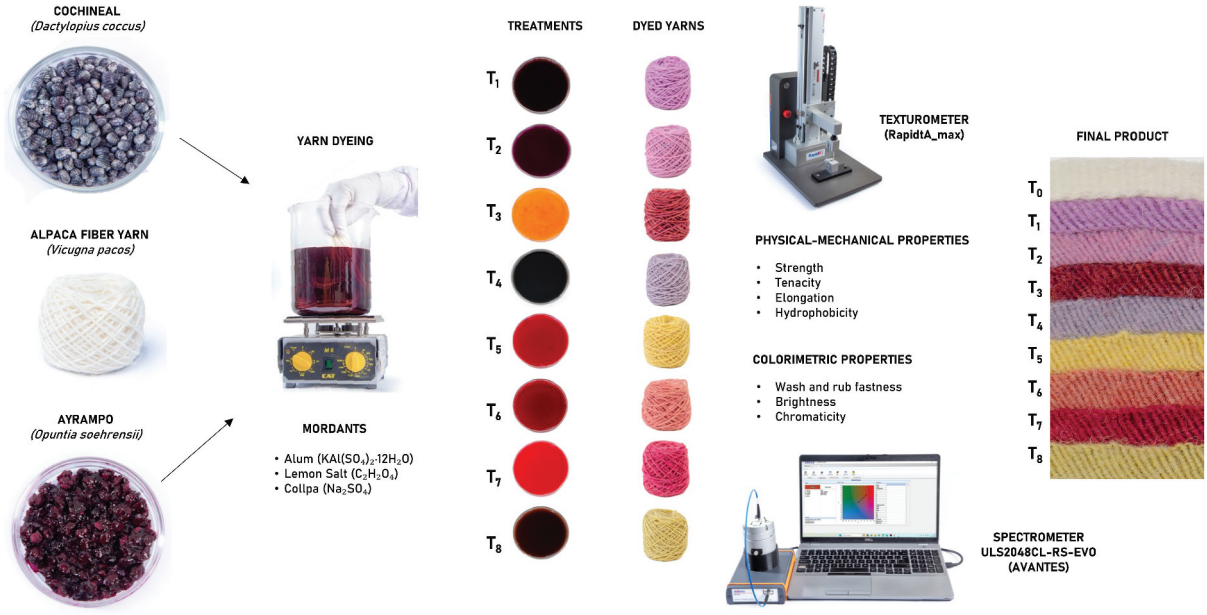

Figure 1. Dyeing process and measurement of physico-mechanical properties of the samples.

$$T = \frac{F_{max}}{A_0} \tag{2}$$

where: F_{max} represents the maximum applied force (N), and A_0 the initial cross-sectional area of the thread (mm^2).

Young's modulus (uppercase E), which indicates the material's stiffness against elastic deformation, was calculated as the slope of the stress – strain curve in the linear region of the mechanical behavior, according to Equation (3):

$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

where: σ represents the applied stress (MPa), and ϵ represents the unit strain.

Colorimetry parameters and dye strength (K/S)

The colorimetric analysis of the dyed threads was performed using the CIELab color space. The parameters measured included the following: lightness (L*, from 0 [black] to 100 [white]), chromatic coordinates a* (green – red axis) and b* (blue – yellow axis), chroma (C*), and hue angle (h°). Spectral measurements were taken with an Avantes ULS2048CL-RS-EVO spectrophotometer (AChroma, which indicates the saturation or intensity of the color, was calculated using the a* and b* coordinates (Equation 4), Avantes, Apeldoorn, the Netherlands), connected to a 50 mm integrating sphere with a halogen light source. The setup was calibrated with the standard illuminant D65 and a 10° viewing angle (Lindon, Holmes, and Tranter 2019).

Chroma (C*), which indicates the saturation or intensity of the color, was computed using the a* and b* coordinates (Equation 4).

$$c^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{4}$$

The hue angle (h°), which shows the color tone, was calculated from the precise chromatic coordinates (Equation 5).

$$h^\circ = arctan(b^*/a^*) \tag{5}$$

The color strength (K/S) was measured using reflectance spectrophotometry, recording the reflectance (R) in the visible spectrum from 400 to 700 nm. To evaluate the dyeing intensity, the Kubelka–Munk equation was applied (Myrick et al. 2011).

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \tag{6}$$

where R represents the reflectance at the wavelength of maximum absorption, K is the absorption coefficient, and S is the scattering coefficient

Color fastness tests

To assess the colorfastness of the dyed threads, tests for wash, rub, and light fastness were performed following standardized ISO procedures.

Strength of the washdo

Wash fastness was evaluated according to ISO 105-C06:2010 (International Organization for Standardization 2010). During testing, the samples were treated in a Launderometer at 40°C for 30 minutes, alongside a multifiber adjacent fabric strip and a detergent solution at a concentration of 4 g/L. Color resistance was assessed by measuring both the color change in the dyed sample and the color transfer to the adjacent multifiber strip. Both effects were visually graded using the grayscale system, where a value of 5 indicates excellent fastness and a value of 1 indicates poor fastness.

Rub resistance

Rubbing fastness was tested following ISO 105-X12:2016 (International Organization for Standardization 2016), using a crockmeter to apply friction to the samples under both dry and wet conditions. During the test, a consistent force of 9 ± 0.2 N was applied to a white cotton reference fabric. The amount of color transfer to the fabric determined the final rating. It was assessed using a grayscale scale, where a rating of 5 indicates excellent fastness and a rating of 1 indicates poor fastness.

Sunlight resistance

To assess color resistance to light, the principles of ISO 105-B02 (International Organization for Standardization 2014) were followed, with the protocol modified by exposing the samples to natural sunlight for three consecutive days, from 8:00 a.m. to 3:00 p.m. Although the original standard uses a xenon arc lamp, this variation was made for practical reasons. Chromatic variation was measured using a ULS2048CL-RS-EVO spectrophotometer to obtain values in the CIELAB color space. The total color change (ΔE) was calculated using the following formula:

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \tag{7}$$

In this formula, subscripts 1 and 2 refer to the sample values before and after exposure to light, respectively.

Hydrophobicity tests and surface analysis

The hydrophobicity of the threads was evaluated by measuring the static water contact angle on 5 cm × 5 cm fabric samples made from the developed threads. The analysis was carried out using the EMACO-I system, an instrument developed by the Center for Biomedical and Environmental Technological Research (CITBM) and protected under patent No. PE20231604. The process involved placing a controlled-volume water droplet on the surface of each sample and measuring the angle between the fabric surface and the tangent to the droplet. This angle reflects water repellency: the larger the angle, the more hydrophobic the surface. To ensure consistent and reliable data, measurements were performed in triplicate at multiple points on each sample, and the average was used to determine a representative contact angle, thereby enabling the accurate characterization of the material's surface properties.

Statistical analysis

To determine the presence of statistically significant differences, the experimental data were analyzed using Analysis of Variance (ANOVA) to assess the effect of different mordants on the physical and mechanical properties, colorimetric parameters (L*, a*, b*, C*, h°), and hydrophobicity of the threads. All tests were conducted in triplicate ($n = 3$), and the results are reported as the mean ± standard deviation (SD). For multiple comparisons between means, the Tukey HSD (Honestly Significant Difference) test was used, with a result considered significant when the probability value was less than $p < .05$. Data processing, analysis, and visualization were performed using R and Python programming languages. However, it should be noted that the small sample size ($n = 3$) provides low statistical power, limits the detection of real differences, and increases sensitivity to outliers, which makes generalizing the results difficult. Consequently, future research is recommended to adopt a replicated experimental design with a considerably larger number of samples (e.g., $n \geq 15$ or $n \geq 30$), which will allow for more rigorous analyses, more consistent hypothesis testing, and the obtaining of solid confidence intervals.

Results

FT-IR spectral analysis of alpaca fiber

Alpaca fibers show the presence of amide groups A, I, II, and III, which are characteristic of protein-based materials. The Amide A band appears between 3100 and 3500 cm^{-1} in the FTIR spectrum and is associated with N – H and O – H vibrations. In the 2850–3000 cm^{-1} range, C – H stretching vibrations are detected. The Amide I region, found around 1600–1700 cm^{-1}, corresponds to the C = O stretching of the peptide bond. The Amide II band, located near 1500–1480 cm^{-1}, involves N – H bending and C – N stretching, reflecting interactions between amino group hydrogens and protein nitrogen atoms. The Amide III region, between 1361 and 1470 cm^{-1}, is mainly related to C – N stretching in amide bonds. This band provides insights into C – N and N – H stretching and bending motions and is sensitive to variations in amino acid side chains and secondary structures. Finally, the region from 1210 to 1290 cm^{-1} corresponds to C – O vibrations typical of proteins.

FT-IR spectral analysis of extracted dyes

Carmine acid – $C_{22}H_{20}O_{13}$

As shown in Figure 2, the peak at 3288 cm^{-1} corresponds to the stretching vibrations of hydroxyl (–OH) and amine (N – H) groups, within the broad band at 3600–3200 cm^{-1}, which reflects hydrogen bonding among carboxyl groups, sugars, and amines. The peaks at 2921 and 2849 cm^{-1} indicate C – H stretching vibrations typical of aliphatic chains. The signal at 1640 cm^{-1} is particularly important, as it combines strong C = O (carboxylate) and C = N (iminium) stretching with possible N – H bending, making it the most representative band of the betalain chromophore. The peak at 1548 cm^{-1} is linked to the Amide II band (N – H bending) and to C = C stretching in the aromatic rings of betacyanin. At 1457 cm^{-1}, bending vibrations of C – H bonds (CH_2 and CH_3) are observed, close to the medium band at 1420–1380 cm^{-1}, with potential contribution from symmetric stretching of the carboxylate group (COO^-). Finally, the peak at 1073 cm^{-1}, within the fingerprint region (1250–1000 cm^{-1}), corresponds to C – O stretching vibrations, confirming the presence of carboxyl groups and the glycosidic bond that links the sugar to the rest of the molecule, along with C – N vibrations. Altogether, these peaks provide a clear spectroscopic fingerprint that confirms the presence of betalain pigments in the sample.

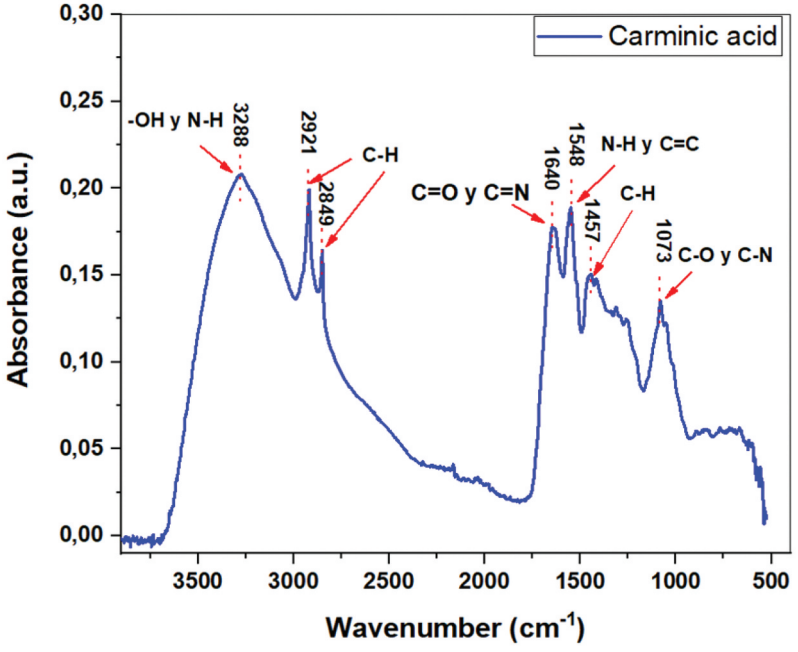

Figure 2. FTIR spectrum of cochineal pigment.

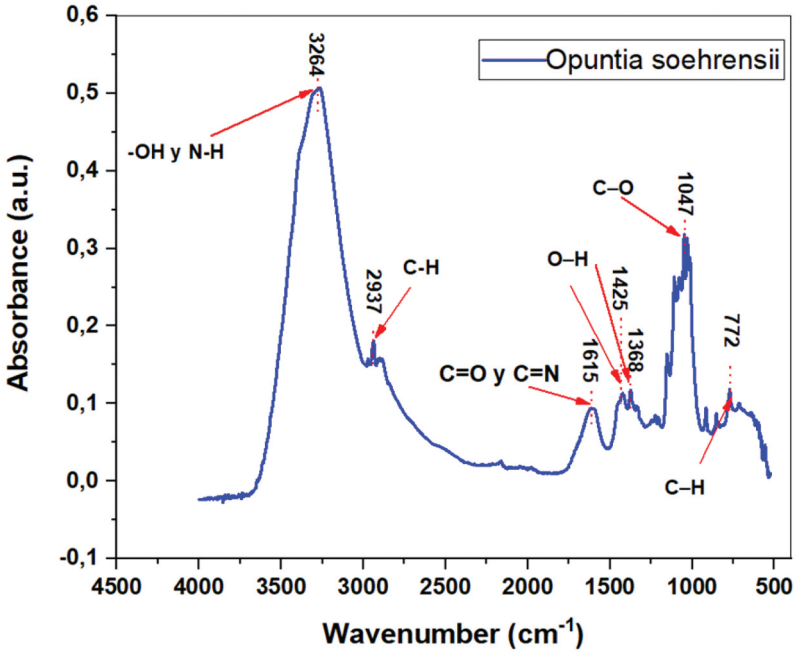

Figure 3. FTIR spectrum of Opuntia soehrensii.

Airampo pigment (betalains). As shown in Figure 3, the peak at 3264 cm^{-1} corresponds to the stretching vibrations of hydroxyl (–OH) and amine (N – H) groups, within the broad region of 3600–3200 cm^{-1}, indicating the presence of carboxyl (–COOH) groups, sugars, and nitrogen-containing compounds. The peak at 2937 cm^{-1} is linked to C – H stretching, typical of aliphatic chains. The signal at 1615 cm^{-1} is especially important, as it reflects the overlap of C = O stretching from the carboxylate group (COO^-) and C = N stretching, making it the most characteristic band of the chromophore responsible for the reddish-violet color. The peaks at 1425 cm^{-1} and 1368 cm^{-1} correspond to O – H bending and symmetric stretching of the carboxylate group, with possible contributions from C – H bending. At 1047 cm^{-1}, within the fingerprint region (1250–1000 cm^{-1}), C – O stretching is observed, confirming carboxylic acid linkages and the glycosidic bond that connects the sugar to the main structure of betanin, along with C – N vibrations. Finally, the peak at 772 cm^{-1} corresponds to out-of-plane C – H bending in substituted rings, supporting the presence of cyclic and aromatic structures. Altogether, these peaks define a clear spectral fingerprint that confirms the presence of betalains, the characteristic pigments of airampo.

FT-IR spectral analysis of mordants

Dehydrated sodium sulfate ($Na_2SO_4 \cdot 10\,H_2O$) - Ccollpa

The FTIR spectrum of the sample (Figure 4) shows distinct peaks at 2921, 1633, 1100, 1000, 707, and 616 cm^{-1}. These signals help identify the main compound, determine its hydration level, and reveal possible impurities. The presence of sulfate ions (SO_4^{2-}) is confirmed by three characteristic bands: the peak at 1100 cm^{-1}, corresponding to the asymmetric stretching of the S = O bond (ν_3 mode), which is the key spectral fingerprint of sulfate; the peak at 1000 cm^{-1}, linked to the symmetric stretching of the S – O bond (ν_1 mode), often seen in crystalline forms; and the peak at 616 cm^{-1}, associated with O – S – O bending (ν_4 mode), supporting the structural identification of the ion. The band at 1633 cm^{-1} indicates hydration, as it corresponds to the H – O – H bending vibration of water, while the peak at 707 cm^{-1} reflects librational vibrations of water molecules within the crystal lattice. Together, these features confirm that the compound is sodium sulfate decahydrate ($Na_2SO_4 \cdot 10\,H_2O$), commonly known as Glauber's salt. However, the peak at 2921 cm^{-1}, located in the C – H stretching region, suggests the presence of an organic impurity, since pure sodium sulfate does not contain carbon – hydrogen bonds. Overall, the FTIR spectrum demonstrates that the sample is hydrated sodium sulfate but not entirely pure, highlighting the usefulness of this technique for both compound identification and quality control.

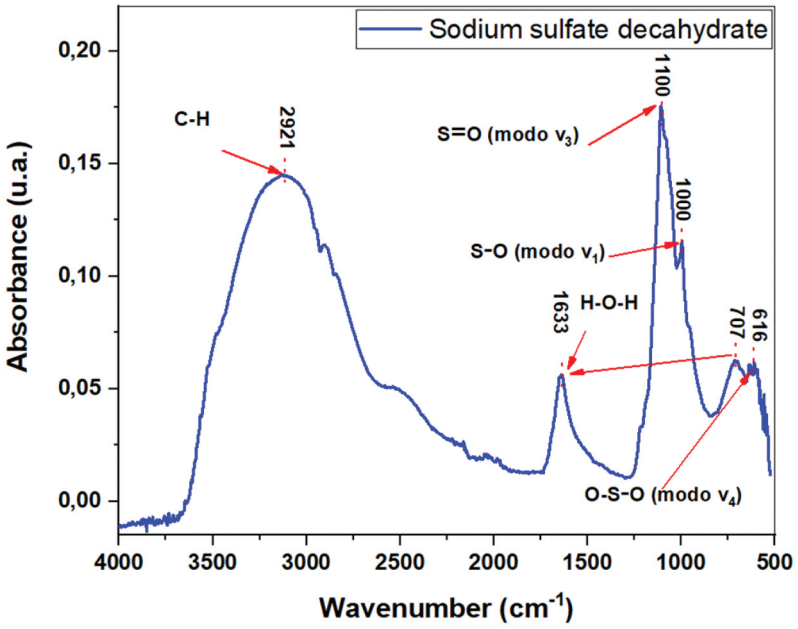

Figure 4. FTIR spectrum of sodium sulfate decahydrate.

Dodecahydrate aluminum potassium sulfate ($KAl(SO_4)_2{\cdot}12\,H_2O$)

The FTIR spectrum of dodecahydrate aluminum potassium sulfate (Figure 5) confirms the presence of water of hydration through three main bands: the peak at 3353 cm^{-1}, corresponding to O – H stretching, shows the presence of water molecules and their involvement in hydrogen bonding; the peak at 1611 cm^{-1}, linked to H – O – H bending, provides clear evidence of molecular water; and the peak at 914 cm^{-1}, associated with librational vibrations, suggests coordination of water molecules with potassium (K^+) and aluminum (Al^{3+}) ions. The sulfate ion (SO_4^{2-}), a structural component of alum, is identified by the peak at 1077 cm^{-1}, which corresponds to asymmetric S = O stretching, and by the peak at 677 cm^{-1}, related to O – S – O bending. Peaks at 2895 and 2485 cm^{-1} indicate impurities, as they are not typical of hydrated aluminum potassium sulfate. The first peak, in the C – H stretching

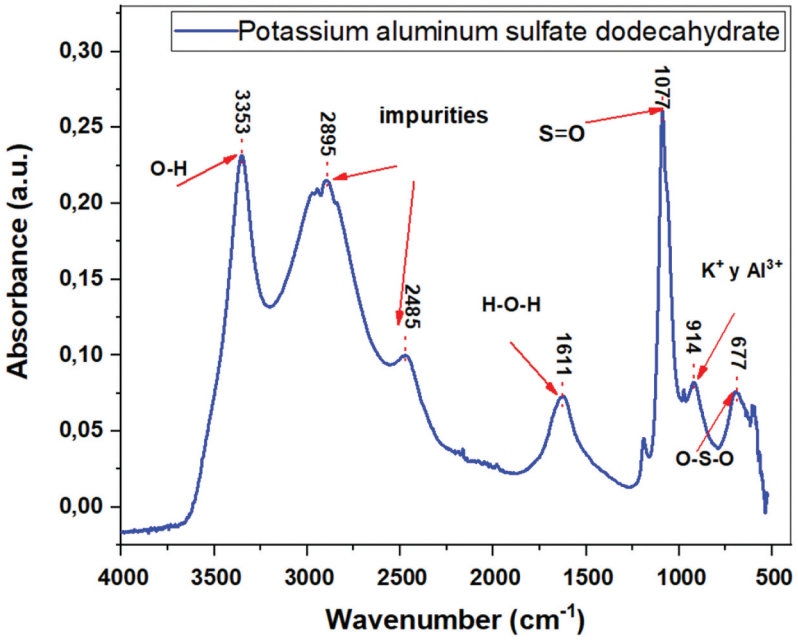

Figure 5. FTIR spectrum of potassium aluminum sulfate.

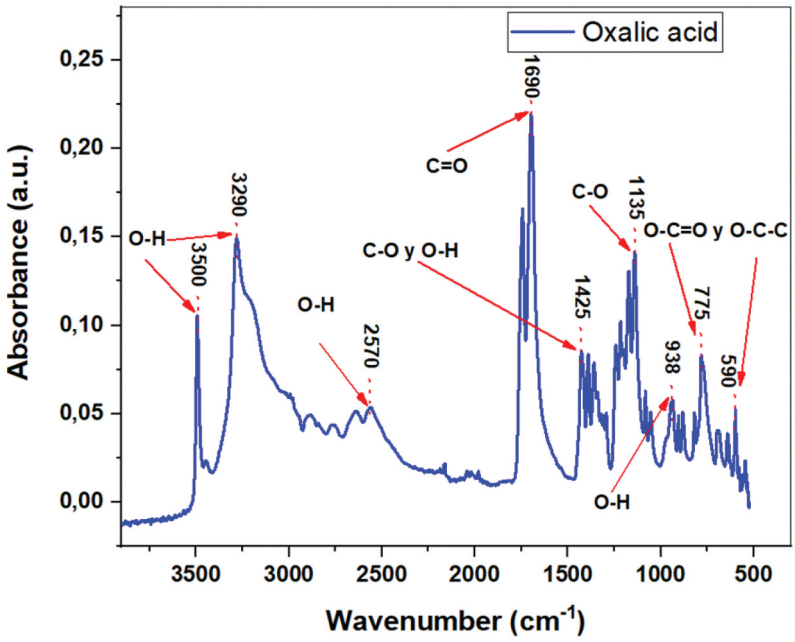

Figure 6. FTIR spectrum of oxalic acid.

region, points to an organic impurity, while the second may result from the same impurity or an adsorbed species. Overall, the FTIR analysis confirms that the sample is hydrated aluminum potassium sulfate, though not completely pure. This highlights the value of FTIR spectroscopy not only for compound identification but also for quality control.

Dihydrate oxalic acid (C2H2O4·2H2O)

As shown in Figure 6, oxalic acid ($C_2H_2O_4$), the simplest dicarboxylic acid, displays a distinctive FTIR spectrum due to its strong hydrogen-bonding capacity, often studied in its dihydrate form ($C_2H_2O_4{\cdot}2\,H_2O$). The spectrum acts as a clear molecular fingerprint. The presence of hydration water is evident from the O – H stretching peak at 3500 cm^{-1}. A notable feature is the broad absorption band in the lower region, with peaks at 3290 cm^{-1} and 2570 cm^{-1}, attributed to O – H stretching of strongly hydrogen-bonded carboxyl groups in a dimer. The sharp peak at 1690 cm^{-1} corresponds to C = O stretching, shifted to lower frequency by hydrogen bonding. In the fingerprint region, the peak at 1425 cm^{-1} is linked to a combination of C – O stretching and O – H in-plane bending, while the band at 1135 cm^{-1} also reflects C – O stretching. The broad absorption at 938 cm^{-1} confirms the dimer structure and is characteristic of out-of-plane O – H bending. Finally, the peaks at 775 cm^{-1} and 590 cm^{-1} complete the spectrum, representing bending and skeletal vibrations such as those of O – C = O and O – C – C bonds. Altogether, these signals clearly confirm that the sample corresponds to dihydrated oxalic acid.

Dyeing chemistry

FTIR spectroscopy of alpaca fiber, dyes, and mordants provided insights into the functional groups involved in the chemistry of dyeing alpaca fibers with natural pigments and inorganic mordants (Table 2). Nine treatments were applied, combining cochineal (carmine acid) and airampo (betalains) as dyes, with or without mordants such as alum ($KAl(SO_4)_2{\cdot}12\,H_2O$), oxalic acid ($C_2H_2O_4$), and collpa ($Na_2SO_4$). In the control group (T_0), which represents the undyed and unmordanted fiber, bands associated with amide groups typical of alpaca keratin were identified. These groups are capable of forming peptide bonds with external compounds. Treatments with cochineal (T_1–T_4) showed signals attributable to hydroxyl (–OH), amino (–NH), carbonyl (C = O), and aromatic structures of carmine acid, which interact with the fiber through peptide bonds (Amide I, II, and III). The addition of alum introduced Al^{3+} and K^{+} ions, acting as bridges between the dye's functional groups and the fiber's

Table 2. Chemical composition of the dyeing according to the treatment applied.

Tratament	Yarn + dye	Mordant	Dyeing Chemistry	Reference
T_0	Alpaca yarn	Unmordanted	Control group: undyed and unmordanted fiber. Alpaca contains proteins with amide groups capable of forming peptide bonds.	Quispe et al. (2025)
T_1	Alpaca yarn + Cochineal (carminic acid)	Unmordanted	Carminic acid contains –OH, N–H, C=O functional groups, and aromatic rings. It binds to the fiber through peptide bonds (Amide I, II, and III).	Haberová et al. (2021)
T_2	Alpaca yarn + Cochineal (carminic acid)	Alum ($KAl(SO_4)_2{\cdot}12H_2O$)	The Al^{3+} and K^+ ions from alum act as a bridge between the dye's functional groups and the fiber's amide groups.	Repon, Islam, and Mamun (2017)
T_3	Alpaca yarn + Cochineal (carminic acid)	Lemon salt (oxalic acid, $C_2H_2O_4$)	Oxalic acid forms hydrogen bonds between the dye and the fiber, enhancing color fixation.	Bechtold and Mussak (2009)
T_4	Alpaca yarn + Cochineal (carminic acid)	Collpa (Na_2SO_4)	The sulfate ion (SO_4^{2-}) participates in chemical interactions through stretching and bending vibrations, promoting the bonding of the dye to the fiber.	Khan et al. (2015)
T_5	Alpaca yarn + Airampo (betalaínas)	Unmordanted	Betalains contain COO^- groups and C=N bonds. The chromophore binds to the fiber through interactions with amide groups.	Strack, Vogt, and Schliemann (2002)
T_6	Alpaca yarn + Airampo (betalaínas)	Alum($KAl(SO_4)_2{\cdot}12H_2O$)	Al^{3+} ions coordinate with the functional groups of betalains, forming complexes that enhance binding to the protein substrate.	Silva (2007)
T_7	Alpaca yarn + Airampo (betalaínas)	Lemon salt (oxalic acid, $C_2H_2O_4$)	Oxalic acid forms hydrogen bonds between betalains and the fiber, facilitating color fixation.	Bechtold and Mussak (2009)
T_8	Alpaca yarn + Airampo (betalaínas)	Collpa (Na_2SO_4)	The sulfate ion contributes to the chemical interaction between the airampo dye and the fiber, promoting its fixation.	Samanta and Konar (2011)

amide groups, aiding fixation. Oxalic acid facilitated the formation of hydrogen bonds between the dye and the fiber. Simultaneously, the sulfate ion (SO_4^{2-}), supplied by collpa, participated in chemical interactions through stretching and bending vibrations, promoting dye binding to the protein substrate. Treatments with airampo (T_5–T_8) revealed carboxylate groups (COO^-) and C = N bonds characteristic of betalains, establishing interactions with the fiber's amide groups. The Al^{3+} ions from alum coordinated with the betalain's functional groups, forming complexes that increase the dye's affinity. Again, oxalic acid promoted hydrogen bonds between the chromophore and the fiber, while the sulfate ion facilitated chemical interactions between the airampo dye and the fiber, thereby enhancing fixation.

Physico-mechanical properties

The values of the physical-mechanical properties of alpaca fibers (Vicugna pacos) for each treatment are listed in Table 3. The analysis of variance (ANOVA) and the Tukey test showed no statistically significant differences ($p > .05$) among the treatments for elongation, maximum force, and tenacity.

The elongation of the fibers ranged from 51.67% (T_4) to 65.00% (T_7). The highest force recorded was between 1.64 N (T_6) and 1.94 N (T_3). Meanwhile, the tenacity of the threads varied from 0.93 MPa (T_6) to 1.10 MPa (T_3). In these three parameters, none of the dyed threads showed a significant difference compared to the undyed control thread (T_0).

In contrast, Young's modulus, which measures the stiffness of the thread, showed statistically significant differences ($p < .05$) between the treatments. The highest value was observed in treatment T_1 (pure Dactylopius coccus) at 5.31 MPa, while the lowest was in treatment T_6 (Opuntia soehrensii + alum) at 1.41 MPa. The control thread (T_0) had a Young's modulus of 4.15 MPa, and the other treatments displayed intermediate values that differed significantly from each other, as indicated by the superscripts in Table 2.

Colorimetry and coloring strength (K/S)

According to the data in Table 4, the colorimetric analysis revealed that cochineal (Dactylopius coccus) exhibits a significantly stronger tinting force than prickly pear (Opuntia soehrensii Britton &

Table 3. Physico-mechanical properties of alpaca (Vicugna pacos) threads, dyed with natural dyes.

Sample	Elongation (%)	Maximum force (N)	Toughness (MPa)	Young's modulus (MPa)
T_0	$57.67^a \pm 15.28$	$1.78^a \pm 0.14$	$1.01^a \pm 0.08$	$4.15^e \pm 0.07$
T_1	$58.67^a \pm 12.34$	$1.67^a \pm 0.20$	$0.94^a \pm 0.11$	$5.31^f \pm 0.17$
T_2	$56.00^a \pm 13.53$	$1.80^a \pm 0.12$	$1.02^a \pm 0.07$	$2.48^c \pm 0.03$
T_3	$61.33^a \pm 3.06$	$1.94^a \pm 0.01$	$1.10^a \pm 0.00$	$2.77^d \pm 0.10$
T_4	$51.67^a \pm 8.50$	$1.81^a \pm 0.11$	$1.02^a \pm 0.06$	$2.78^d \pm 0.04$
T_5	$53.67^a \pm 5.86$	$1.77^a \pm 0.12$	$1.00^a \pm 0.07$	$2.66^d \pm 0.03$
T_6	$64.33^a \pm 3.51$	$1.64^a \pm 0.09$	$0.93^a \pm 0.05$	$1.41^a \pm 0.07$
T_7	$65.00^a \pm 2.00$	$1.68^a \pm 0.16$	$0.95^a \pm 0.09$	$2.34^c \pm 0.08$
T_8	$59.00^a \pm 13.45$	$1.78^a \pm 0.21$	$1.01^a \pm 0.12$	$1.80^b \pm 0.05$

T_0, undyed yarn (white); **T_1**, yarn dyed with cochineal (*Dactylopius coccus*); **T_2**, **T_3**, and **T_4**, yarns dyed with cochineal plus mordants (alum, citric acid, and collpa, respectively); **T_5**, yarn dyed with airampo (*Opuntia soehrensii* Britton & Rose); **T_6**, **T_7**, and **T_8**, yarns dyed with airampo plus mordants (alum, citric acid, and collpa, respectively). Results are expressed as mean ± standard deviation ($n = 3$), and superscripts with different letters in columns indicate statistically significant differences ($p < .05$).

Table 4. Colorimetry parameters.

Muestra	L*	*a**	*b**	C*	h°	K/S
T_0	91.59 ± 0.48^g	02.39 ± 0.04^a	07.39 ± 0.13^c	7.77 ± 0.14^a	72.09 ± 0.06^c	0 ± 0.0
T_1	56.80 ± 0.69^d	26.35 ± 2.34^{de}	-09.76 ± 0.37^a	28.11 ± 2.22^{de}	339.60 ± 1.68^f	2.67 ± 0.11^d
T_2	57.63 ± 0.28^d	24.75 ± 0.40^d	-03.77 ± 0.26^b	25.04 ± 0.36^d	351.33 ± 0.73^g	2.76 ± 0.12^d
T_3	37.28 ± 0.94^a	31.45 ± 1.71^f	6.94 ± 0.73^c	32.21 ± 1.83^f	12.41 ± 0.67^a	1.06 ± 0.13^c
T_4	58.54 ± 0.53^d	10.41 ± 0.95^c	-04.90 ± 0.28^b	11.50 ± 0.97^b	334.74 ± 0.97^e	2.88 ± 0.15^d
T_5	70.35 ± 1.01^f	04.48 ± 0.39^b	27.71 ± 3.17^f	28.07 ± 3.16^{de}	80.77 ± 0.91^d	0.19 ± 0.28^{ab}
T_6	52.45 ± 0.63^c	27.85 ± 0.23^e	13.77 ± 0.64^d	31.08 ± 0.11^{ef}	26.31 ± 1.24^b	0.27 ± 0.46^{ab}
T_7	40.17 ± 1.65^b	37.78 ± 1.72^g	7.26 ± 1.38^c	38.48 ± 1.78^g	10.87 ± 1.92^a	0.35 ± 0.19^{ab}
T_8	67.50 ± 1.98^e	02.73 ± 0.20^{ab}	17.37 ± 3.64^e	17.60 ± 3.57^c	80.75 ± 2.36^d	1.02 ± 0.23^c

L*, luminosity; C*, chromaticity; h°, hue. T0, undyed thread (white); T1, thread dyed with cochineal (Dactylopius coccus); T2, T3, and T4, threads dyed with cochineal + mordants (alum, lemon salt, and collpa, respectively); T5, thread dyed with prickly pear (Opuntia soehrensii Britton & Rose); T6, T7, and T8, threads dyed with prickly pear + mordants (alum, lemon salt, and collpa, respectively). Results expressed as mean ± standard deviation ($n = 3$), and superscripts with different letters in columns indicate significant differences ($p < .05$).

Rose), particularly in treatments that incorporate mordants. The highest K/S values were recorded in treatments with cochineal and collpa mordants (T_4: 2.88 ± 0.15) and alum (T_2: 2.76 ± 0.12), producing intense shades. In contrast, treatments with prickly pear showed a considerably lower tinting affinity, with K/S values ranging from 0.19 to 0.35 in T_6, T_7, and T_5, resulting in lighter and less saturated colors. The only prickly pear treatment that exceeded a value of 1.00 was T_8 (prickly pear + collpa: 1.02 ± 0.23), although still below the values obtained with cochineal. Regarding brightness (L*), treatments with cochineal produced darker colors, with T_3 (cochineal + lemon salt: 37.28 ± 0.94) standing out as the lowest, while T_4 (cochineal + collpa: 58.54 ± 0.53) showed the highest brightness within this group. Conversely, treatments with prickly pear showed higher brightness values, such as T_5 (airampo: 70.35 ± 1.01) and T_8 (airampo + collpa: 67 ± 1.98), indicating that prickly pear tends to produce lighter, warmer shades compared to cochineal, which creates deeper, cooler hues. The a* coordinate (red – green) reached its maximum value in T_7 (airampo + lemon salt: 37.78 ± 1.72), followed by T_3 (cochineal + lemon salt: 31.45 ± 1.71), indicating a high red component intensity under this mordant in both dyes. Regarding the b* coordinate (yellow – blue), the highest value was observed in T_5 (pure airampo: 27.71 ± 3.17), while the lowest corresponded to T_1 (pure cochineal: −9.76 ± 0.37), indicating a marked blue inclination in treatments with cochineal. The hue angle (h°) also varied depending on the type of mordant and dye: treatments with cochineal T_1 and T_2 were located in the cool magenta region (339.60° and 351.33°, respectively), while T_3 shifted toward a warm red (12.41°). In contrast, treatments with prickly pear T_5 and T_8 showed angles close to 80°, confirming the generation of warm tones characteristic of this dye. In terms of chroma (C*), treatment T_7 (airampo + lemon salt) had the highest value (38.48 ± 1.78), followed by cochineal treatments T_1 (28.11 ± 2.22) and T_2 (25.04 ± 0.36), indicating high saturation in these cases. The statistical analysis ($p < .05$), indicated by superscript letters in the table columns, confirmed significant differences between treatments for each evaluated colorimetric parameter, demonstrating that each combination of dye and mordant produces a unique and reproducible chromatic profile on alpaca fiber.

Hydrophobicity properties and surface analysis

Dyeing treatments significantly changed the surface properties of the alpaca fiber, as shown by contact angle analysis (Table 5). A key finding was the increase in hydrophobicity in the sample dyed with pure cochineal (T_1), which showed the highest contact angle (97.22° ± 1.08). This could be due to the deposition of waxy or lipid components from the dye extract on the fiber surface, resulting in increased water resistance. In contrast, adding mordants altered this property, since treatments with cochineal and mordants showed lower contact angles: T_2 (alum) with 94.09° ± 1.25, T_3 (lemon salt) with 93.16° ± 0.88, and T_4 (collpa) with 95.08° ± 1.01, indicating that the salts might have interfered with the surface layer. Pure airampo (T_5) had a contact angle of 94.08° ± 0.95. In comparison, treatments with mordants further decreased hydrophobicity: T_6 (alum) with 93.71° ± 0.56, T_7 (lemon salt) with 92.95° ± 0.93, and T_8 (collpa) with 89.2° ± 1.11, the

Table 5. Contact angle of dyed alpaca threads.

Sample	Minimum (°)	Maximum (°)	Mean (°) ± SD
T_0	88.92	91.46	89.98^{a} ± 1.18
T_1	95.87	98.60	97.22^{e} ± 1.08
T_2	92.55	95.57	94.09^{bc} ± 1.25
T_3	92.62	94.71	93.16^{b} ± 0.88
T_4	93.88	96.56	95.08^{c} ± 1.01
T_5	92.77	95.27	94.08^{bc} ± 0.95
T_6	93.13	94.66	93.71^{b} ± 0.56
T_7	92.29	94.53	92.95^{b} ± 0.93
T_8	88.26	90.90	89.2^{a} ±1.11

T_0, undyed thread (white); T_1, thread dyed with cochineal (Dactylopius coccus); T_2, T_3, and T_4, threads dyed with cochineal + mordants (alum, lemon salt, and collpa, respectively); T5, thread dyed with prickly pear (Opuntia soehrensii Britton & Rose); T_6, T_7, and T_8, threads dyed with prickly pear + mordants (alum, lemon salt, and collpa, respectively). Results expressed as mean ± standard deviation ($n = 3$), and different superscript letters in columns indicate significant differences ($p < .05$).

last being the lowest value, with a slightly hydrophilic behavior (angle <90°). The untreated fiber (T_0) had a contact angle of 89.98° ± 1.18, serving as a baseline. Variance analysis and Tukey's test ($p < .05$) confirmed significant differences among treatments, enabling their grouping: T0 and T8 formed the group with the lowest hydrophobicity; T_2, T_3, T_5, T_6, and T_7 formed an intermediate group; and T_4 and T_1 showed the highest hydrophobicity, with T_1 being notably higher than the others. These findings highlight that both the type of dye and the mordant used largely influence the surface properties of the alpaca fiber.

Color solidity

Wash fastness (ISO 105 C06: 2010)

The wash fastness test assessed color stability in dyed alpaca threads by examining two key factors: color fading within the sample itself and color transfer to neighboring fabrics. The results, shown in Table 6, indicated a low retention of dye in the fiber after washing, especially in samples dyed with cochineal (T_1, T_2, T_4) and airampo (T_5, T_6, T_8), which experienced a "severe" color change, with ratings between 1 and 1–2. The samples treated with lemon salt as a mordant, T_3 (cochineal) and T_7 (airampo), displayed a "considerable" change, rated as 2 and between 1 and 2, respectively. Despite this low fixation, the color transfer was minimal across all samples. All dyed fabrics received a "light" stain rating, with consistent numerical scores between 4 and 5, showing that the dyes did not significantly stain neighboring textiles during the wash cycle. Overall, although the natural dyes demonstrated low stability in the alpaca fiber, leading to noticeable fading, they posed a very low risk of color transfer to other garments during domestic washing.

Colorfastness to rubbing (ISO 105-X12:2016)

The rub fastness test, which assesses a color's resistance to transfer through friction to another surface, showed significant differences among the natural dyes used (Table 7). Threads dyed with annatto (T_5-T_8), regardless of the mordant applied, performed excellently, displaying light staining in both dry and wet conditions, with visual ratings between 4 and 4.5, indicating good color fixation and a low tendency for abrasion loss. In contrast, cochineal dyes (T_1-T_4) demonstrated variable and generally poor performance. Pure cochineal (T_1) yielded promising results in dry conditions ("Light," rating of 4), but its resistance decreased markedly when wet, with a notable

Table 6. Results of the wash durability assessment.

Sample	Color change (degradation)	Interpretation of the chang	Color transfer (Staining)	Staining interpretation
T_1	1–2	Severe	4–5	Light
T_2	1–2	Severe	4–5 a 5	Light
T_3	2	Considerable	4–5 a 5	Light
T_4	1	Severe	4–5	Light
T_5	1	Severe	4–5 a 5	Light
T_6	1	Severe	4–5 a 5	Light
T_7	1–2	Considerable	4–5 a 5	Light
T_8	1	Severe	4–5 a 5	Light

T_1, thread dyed with cochineal (Dactylopius coccus); T_2, T_3, and T_4, threads dyed with cochineal + mordants (alum, lemon salt, and collpa, respectively); T_5, thread dyed with ayrampo (Opuntia soehrensii Britton & Rose); T_6, T_7, and T_8, threads dyed with ayrampo + mordants (alum, lemon salt, and collpa, respectively).

Table 7. Results of the wash durability test by rubbing.

Sample	Color Change (Degradation)	Interpretation of the Chang	Color Transfer (Staining)	Staining Interpretation
T_1	4	Light	3	Notable
T_2	1–2	Considerable	1–2	Considerable
T_3	2	Considerable	2	Considerable
T_4	2	Considerable	2	Considerable
T_5	4	Light	4–5	Light
T_6	4	Light	4–5	Light
T_7	4	Light	4	Light
T_8	4	Light	4	Light

T_1, thread dyed with cochineal (Dactylopius coccus); T_2, T_3, and T_4, threads dyed with cochineal + mordants (alum, lemon salt, and collpa, respectively); T_5, thread dyed with ayrampo (Opuntia soehrensii Britton & Rose); T_6, T_7, and T_8, threads dyed with ayrampo + mordants (alum, lemon salt, and collpa, respectively).

Table 8. Evaluation of sunlight fastness in alpaca yarns.

Sample	Natural dye	Exposure time (h)	ΔE* (CIELAB)	Technical observations
T_1	4	25	16,98	Low fastness. Loss of intensity
T_2	1–2	25	7,38	Moderate fastness. More stable color
T_3	2	25	5,66	Good fastness. Improved color stability
T_4	2	25	6,96	Moderate to good fastness. Better tone retention
T_5	4	25	20,45	Very low fastness. Severe fading
T_6	4	25	16,29	Low fastness. Noticeable discoloration
T_7	4	25	12,99	Moderate fastness. Better performance than T_6 and T_8
T_8	4	25	15,30	Low fastness. Evident color change

T_1, thread dyed with cochineal (Dactylopius coccus); T_2, T_3, and T_4, threads dyed with cochineal + mordants (alum, lemon salt, and collpa, respectively); T_5, thread dyed with airampo (Opuntia soehrensii Britton & Rose); T_6, T_7, and T_8, threads dyed with airampo + mordants (alum, lemon salt, and collpa, respectively).

staining ("Notable," rating of 3). The samples with mordants (T_2, T_3, and T_4) exhibited poor fastness, with staining rated as "Considerable" in both conditions and low ratings between 1 and 2, indicating that the complexes formed between the dye and mordants do not offer sufficient resistance to mechanical friction.

Durability in sunlight

The assessment of sunlight fastness on alpaca threads dyed with natural dyes (Table 8) revealed varying levels of color stability after 25 hours of exposure, measured by the color difference (ΔE*), where lower values indicate better color retention. In the case of cochineal dyes, different fastness levels were observed: the undyed thread (T_1) showed the most significant color change with a ΔE* of 16.98, indicating low fastness and loss of intensity; in contrast, the use of mordants improved stability, with the thread treated with lemon salt (T_3) being the most stable with a ΔE* of 5.66 and followed by threads with collpa (T_4) and alum (T_2), which demonstrated moderate fastness with ΔE* values of 6.96 and 7.38, respectively. Conversely, threads dyed with airampo generally exhibited lower fastness: the undyed thread (T_5) recorded the most significant color change among all samples with a ΔE* of 20.45, indicating very low fastness and significant fading. Although mordants reduced the color change, the fastness remained low, with the thread treated with lemon salt (T_7) performing the best within this group, with a ΔE* of 12.99. Threads treated with collpa (T_8) and alum (T_6) reached ΔE* values of 15.30 and 16.29, respectively, confirming their limited stability against sun exposure.

Discussion

FT-IR spectral characterization of alpaca fiber

FT-IR spectral analysis of alpaca fiber confirms the presence of characteristic bands associated with protein structures, such as amide A (3100–3500 cm^{-1}), amide I (1600–1700 cm^{-1}), amide II (1480–1500 cm^{-1}), and amide III (1361–1470 cm^{-1}). It also shows signals related to C-H (2850–3000 cm^{-1}) and C-O (1210–1290 cm^{-1}) bonds. These bands indicate the keratin composition of the fiber and help infer structural features, such as secondary structure and the placement of functional groups in amino acid side chains. The results align with those reported by Quispe et al. (2025), who identified key spectral peaks at 1473, 1419, and 1287 cm^{-1} using m-FTIR-ATR spectroscopy, associated with C-N and C-H bonds. These bands partly helped distinguish alpaca fiber from other animal fibers such as llama and mohair, although spectral overlaps were observed that limit visual discrimination.

FT-IR spectral characterization of natural pigments

The FT-IR spectral analysis of the natural pigments carminic acid and airampo confirmed their chemical structures by identifying key functional groups. Both compounds displayed signals from hydroxyl, amine, and C-H bonds; however, the region near 1600 cm^{-1} was crucial in differentiating their chromophores.

In the case of carminic acid, the peak at 1640 cm^{-1} confirms the presence of C = O and C = N bonds, consistent with its anthraquinone structure. Additionally, bands were detected at 3288 cm^{-1} (hydrogen bonds), 2921 and 2849 cm^{-1} (aliphatic chains), and 1073 cm^{-1} (C-O bonds), which verify the existence of

carboxyl groups, aromatic rings, methyl groups, and glycosidic bonds. Similar results were reported by Chieli et al. (2016) and Haberová et al. (2021), who also verified the structure of carminic acid through spectroscopic analysis.

The FT-IR spectral analysis of the airampo pigment showed a prominent peak at 1615 cm^{-1}, linked to the characteristic chromophore of betalaínas, along with signals associated with carboxylate groups and cyclic structures. These results confirm the dye's identity as a betalaína, consistent with specialized literature. Similar findings were reported by Flint et al. (2024), who also used FT-IR to identify vibrations corresponding to important functional groups, such as hydroxyl, C-H, C = C, and C = O, all of which align with the chromophoric structure of betalaínas. Additionally, the authors pointed out the presence of C-O-C and C-N bonds, indicating a glycosidic part in the molecule, which further supports identifying the compound as a glycosylated betalaína.

FT-IR spectral characterization of mordants

FT-IR spectroscopy enabled the precise identification of the chemical makeup of mordants, collpa, alum, and oxalic acid, also revealing impurities that could influence their performance in dyeing processes. Each spectrum acts as a unique molecular fingerprint, confirming the structural identity of the compounds being analyzed.

In the present study, FTIR spectroscopic analysis confirmed the presence of anhydrous sodium sulfate ($Na_2SO_4 \cdot 10\ H_2O$), commonly known as Glauber's salt, by identifying characteristic bands of the sulfate ion and vibrations related to hydration water. The signals observed in the regions of 1100–1080 cm^{-1} (ν_3) and 980–960 cm^{-1} (ν_1) correspond to the typical stretches of the SO_4^{2-} ion, while the bands at 3400–3200 cm^{-1} and 1650–1600 cm^{-1} relate to the stretching and bending of hydration water, respectively. These results align with those reported by Socrates (2004), who describes these bands as representative of hydrated sodium sulfate.

However, an additional signal was detected in the 2950–2850 cm^{-1} region, attributed to aliphatic C – H stretching, which is not expected in pure sulfates. This finding suggests the presence of organic impurities in the analyzed sample, possibly from manufacturing residues or contamination during storage. Such a discovery is important in textile dyeing processes, as these impurities could affect the interaction between the dye and the fiber, leading to inconsistencies in dyeing results.

The results from the FTIR analysis of dodecahydrate **aluminum and potassium sulfate** ($KAl(SO_4)_2 \cdot 12\ H_2O$) closely match those reported by Wijayati et al. (2021), especially in identifying characteristic sulfate ion bands and the hydrated alum structure. Both studies exhibit absorption bands corresponding to the stretching vibrations of the S = O group (1195 cm^{-1} and 1077 cm^{-1}), along with signals for S – O bonds (933 cm^{-1}) and Al – O bonds (737 cm^{-1}), confirming the presence of these functional groups in the sample. Furthermore, peaks in the 750–400 cm^{-1} range support vibrations typical of the Al – O bond, while sulfate ion (SO_4^{2-}) vibrational modes appear in the ranges of 468–471 cm^{-1}, 603–608 cm^{-1}, 657–686 cm^{-1}, 1104–1115 cm^{-1}, and 1237–1247 cm^{-1}, aligning with the spectral patterns described in that reference.

The results from this study confirm that dihydrate oxalic acid ($C_2H_2O_4 \cdot 2\ H_2O$), commonly known as lemon salt, exhibits a distinctive FTIR spectrum characterized by intense bands that confirm its dicarboxylic structure and the presence of O – H bonds associated with both the carboxyl group and the hydration water. The signals observed in the regions of 1690–1720 cm^{-1} (C = O stretching), 3200–3500 cm^{-1} (O – H stretching), 1400–1450 cm^{-1} (O – H deformation), and 1050–1300 cm^{-1} (C – O vibrations) perfectly match the spectral assignments reported by Merck, reinforcing the identification of the compound's structure. The spectral results of dihydrate oxalic acid are in agreement with those reported by Merck (2025), confirming its molecular structure. The absence of impurities indicates a higher purity compared to other mordants, such as alum and collpa. Its synthetic origin and refinement explain the clear spectral features, making it a more stable and effective mordant. Additionally, the formation of dimers through hydrogen bonds suggests a high capacity for molecular interaction, which is key in fixing dyes onto textile and biopolymer substrates.

Dyeing chemistry

About the chemical mechanisms involved in dyeing alpaca yarn with cochineal (carminic acid) and airampo (betalains), using different mordants: alum, lemon salt (oxalic acid), and collpa (sodium sulfate). The control group (T_0) confirms that alpaca fiber, being proteinaceous, contains amide groups capable of forming peptide bonds, which provides the basis for interaction with natural dyes (Quispe et al. 2025).

The treatments applied with **cochineal** (T_1–T_4) demonstrated that carminic acid binds to the fiber through peptide bonds, utilizing the reactivity of its functional groups (–OH, –NH, and C = O), as well as the π–π interaction of its aromatic rings (Quispe et al. 2025). In treatment T2, the addition of alum as a mordant introduces metallic ions Al^{3+} and K^+, which act as coordinating bridges between the dye and the fiber, a mechanism widely documented by Haberová et al. (2021). Meanwhile, oxalic acid (T3) promotes color retention through the formation of hydrogen bonds, as described in the technical manual by Bechtold and Mussak (2009). Finally, the use of sodium sulfate (T4) encourages chemical interaction through the vibrations of the SO_4^{2-} ion, in accordance with the findings of Khan et al. (2015).

In treatments with **airampo** (T_5–T_8), it was observed that betalaínas bind to the fiber through specific interactions with amide groups, utilizing the presence of COO^- and C = N links, as described by Strack, Vogt, and Schliemann (2002). In treatment T6, alum again acts as a coordinating agent, introducing metal ions that form stable complexes with the dye, which enhances its adherence to the fiber (Silva 2007). Meanwhile, oxalic acid (T_7) and sodium sulfate (T_8) continue to serve as promoters of hydrogen bonds and ionic interactions, respectively, in accordance with the mechanisms reported by Bechtold and Mussak (2009) and Samanta and Konar (2011). Additionally, the analysis identifies three key dimensions that future research should address: water consumption, with the need to implement technical improvements that optimize its use and reduce environmental impacts; toxicity, through more detailed comparative studies on alum to ensure safety in various applications; and scalability, focused on the limited availability of ayrampo and its orientation toward artisanal and sustainable value chains.

Physical-mechanical properties

Dyeing alpaca threads with natural dyes, such as cochineal and airampo, does not negatively impact their fundamental mechanical properties, including elongation, maximum strength, and toughness. However, significant differences were observed in the Young's Modulus, indicating that the dyeing process subtly changes the material's stiffness. Although structural resistance is maintained, this change affects the tactile perception of the thread, a key aspect in evaluating high-end textiles where sensory quality is as important as durability. The results align with those of Jankowska et al. (2021), who compared the physico-mechanical properties of alpaca, sheep, and goat threads. In that comparison, the alpaca thread showed a significantly higher breaking force (3036 cN) compared to the sheep thread (2314 cN). However, its toughness was the lowest among the three types evaluated (50.03 MPa), though this difference was not statistically significant. These data suggest that, while alpaca thread can withstand greater loads before breaking, its ability to absorb energy before fracture is limited.

The Young's modulus of the alpaca thread was the lowest among the materials analyzed by Jankowska et al. (2019), with a value of 340.82 MPa, confirming its high elasticity. In this study, it was observed that dyeing with pure cochineal (T_1) increased this modulus to 5.31 MPa, compared to 4.15 MPa for the undyed thread. This increase can be attributed to the interaction of carminic acid with fiber proteins through hydrogen bonds, forming a stronger internal network, as indicated by the FTIR spectra. In contrast, using alum-impregnated airampo as a mordant (T_6) reduced the stiffness to 1.41 MPa, possibly due to hydration of the complex created with the aluminum ion (Al^{3+}), which results in a more flexible internal structure.

The ability to dye alpaca yarns without losing their mechanical strength offers a strategic advantage for the sustainable textile industry. Additionally, controlling stiffness through the choice of dyes and mordants enables the design of products with specific textures. Yarns treated with cochineal can be used in structured textiles, such as upholstery, while those dyed with annatto and alum are better suited for soft, flowing garments. Future research could investigate the molecular interactions between dyes and fibers in greater

detail, as well as the impact of factors such as mordant concentration and temperature on Young's modulus. This would help optimize the use of natural resources and broaden design options in the high-quality textile market.

Colorimetric performance

The comparative analysis of the natural dyes cochineal (Dactylopius coccus) and airampo (Opuntia soehrensii) demonstrated their ability to produce a diverse and valuable color range on alpaca fiber. Cochineal, in the presence of oxalic acid (lemon salt), yielded dark shades with T_3 values of 37.28. At the same time, its intense red tones reached a* value of up to 31.45, reflecting high saturation and strong dye affinity. In contrast, airampo generated warm and bright tones, with L* values exceeding 70.35, indicating high reflectance and visual clarity. Mordants played a decisive role in modulating hue, acting as catalysts for significant chromatic variations. This behavior aligns with reports by Lozano, Quispe-Quispe, and Vilcanqui-Pérez (2024) and Shahmoradi Ghaheh, Moghaddam, and Tehrani (2021), who also documented the direct effect of mordants on the chromatic expression of natural dyes. Specifically, oxalic acid caused a shift in cochineal's hue toward a cool magenta (h° = 12.41), while sodium sulfate (collpa) promoted a warmer red in airampo (h° = 80.75). These findings not only validate traditional dyeing knowledge but also demonstrate that each specific combination of dye and mordant produces a distinctive and reproducible chromatic profile on protein substrates, such as alpaca. Although the study focused on initial colorimetric parameters, the results open new avenues for research aimed at standardizing artisanal techniques and optimizing the color palette. It is recommended to deepen the understanding of the relationship between the pH of the dyeing medium and color variations, explore synergies between mordants, and analyze the influence of the dye's molecular structure on its dyeing properties. These approaches would help advance toward sustainable, reproducible, and scientifically grounded dyeing practices.

Hydrophobicity and surface properties

The results of the current study show a significant increase in the hydrophobicity of dyed alpaca fiber with pure cochineal (T_1), consistent with the literature, which describes the ability of certain natural dyes to modify the surface energy of fibers. This finding suggests that, beyond coloring, the cochineal extract deposits compounds with water-repellent properties on the protein surface, which relates to what Naebe et al. (2010) observed regarding the natural hydrophobicity of wool, which persists even after specific treatments. This suggests that the surface properties of protein fibers can be either naturally resistant or intentionally modified through the addition of external substances. The contact angle increased from 89.98° to 97.22° in sample T_1, exceeding the hydrophobicity typically attributed to lanolin in fibers like wool, suggesting that cochineal creates an extra layer of lipidic or waxy compounds that boost water resistance. This surface modification, achieved simply through dyeing, adds new functionality to the fiber, supporting the statement by Sureshkumar et al. (2021) on the importance of managing hydrophobicity to broaden the applications of natural fibers. The study also demonstrates that the addition of saline mordants reduces the hydrophobic effect, aligning with the proposal by Sureshkumar et al. (2021), which suggests that the fibers' natural hydrophilicity limits their use in specific applications and that chemical treatments can modify this property. In this case, the ionic interaction of the salts with the protein surface appears to have disrupted or altered the protective layer created by cochineal. This matches Brack et al. (1999)'s description of how removing surface lipids can decrease hydrophobicity and improve wettability, making the fiber more receptive to water and other agents. Although mordants do not remove the cochineal layer, their presence changes the surface chemistry in a way that counteracts the hydrophobic effect, possibly due to changes in surface topography and the addition of functional groups that promote wettability. A limitation of the study is that it did not evaluate the durability of the hydrophobic effect, an aspect that Brack et al. (1999) consider key when referring to the firm and stable adsorption of substances that durably modify the fiber's surface properties. Future research should focus on the stability of hydrophobicity through washing and wear cycles to determine if the effect is comparable to more permanent treatments described in the literature.

Color solidity

Although favorable results were achieved in terms of mechanical properties and colorimetry, the low wash fastness remains the primary challenge for the commercial use of the evaluated natural dyes. Most treatments showed significant color degradation, with ratings of 1 to 2 on the grayscale, indicating that the dye easily comes off the fiber during washing. However, the transfer of color to other garments was minimal (ratings of 4–5 to 5), suggesting that the dye released does not cause secondary stains.

Regarding the rubbing fastness, the results were mixed: the threads dyed with airampo showed excellent resistance (ratings of 4 to 4–5), while those dyed with cochineal, especially those treated with mordants, exhibited limited performance. This low color fixation emphasizes the need to improve the dyeing process.

The current scientific literature suggests promising alternatives, including the use of mordants, ultrasound-assisted technologies, and green chemistry approaches, to improve the color durability of natural fibers. In this context, the results of this study provide a solid comparative foundation, supporting the application of these innovative techniques to alpaca fiber. Similar findings were reported by Eyupoglu et al. (2024), who assessed color fastness in Merino wool dyed with a natural extract of Aesculus hippocastanum using a microwave-assisted method and mordanting with aluminum and potassium sulfate. In that study, wash fastness increased from a low rating (2) to scores between 3 and 4. In contrast, rub fastness improved from 2–3 to 4, demonstrating that the concentration of the mordant and exposure time are critical factors in color fixation. These findings emphasize the importance of optimizing mordanting conditions to boost color resistance in protein fibers dyed with natural dyes. Additionally, the results open the possibility of guiding future research toward incorporating innovative methods, including plasma use and various emerging technologies, to help improve color fastness in natural fiber dyeing processes. Likewise, there is a need to further explore the use of biomordants and nontoxic alternatives to optimize color fixation and ensure more sustainable and safer processes.

Solidity in sunlight

The resistance of alpaca threads dyed with cochineal and airampo to sunlight is heavily affected by the use of mordants. After 25 hours of exposure, it was observed that mordants help reduce color loss, leading to better fixation of the cochineal pigments. Specifically, the sample without a mordant showed significant degradation ($\Delta E^* = 16.98$). Conversely, treatment with lemon salt (citric acid) greatly enhanced color stability ($\Delta E^* = 5.66$), likely due to the formation of complexes that resist radiation. Collpa and alum mordants also helped, but to a lesser extent. On the other hand, threads dyed with airampo proved more susceptible to photodegradation, even with mordants; lemon salt remained the most effective ($\Delta E^* = 12.99$), although it did not provide sufficient colorfastness. This suggests that the airampo pigment is more sensitive to solar radiation. These findings align with those of Ali, Harmon, and Kirkham (2025), who reported that treatment with lemon juice and a low dye concentration (3 g/L) enhances lightfastness in cotton dyed with indigo and woad, and that using thiourea as a reducing agent provides better protection than fructose.

Conclusions

The study demonstrated that dyeing alpaca yarns with natural dyes obtained from cochineal (Dactylopius coccus) and prickly pear (Opuntia soehrensii), combined with traditional mordants, is a practical alternative for the textile industry. This method preserves the physical and mechanical properties of the fiber, yielding a rich and varied color palette. The treatments did not cause significant changes in parameters such as elongation, maximum force, or tensile strength, indicating that the fiber's internal structure remained intact. However, notable differences were observed in the Young's Modulus, indicating a subtle change in the fiber's stiffness and texture.

From a colorimetric perspective, the results were clear and consistent. Cochineal produced deep red shades, with an a^* value reaching 34.95, while airampo yielded warm, bright yellow hues, with L^* values reaching up to 70.19. The mordants used, including alum, oxalic acid (also known as lemon salt), and collpa, acted as effective color modifiers, expanding the range of shades produced. A notable finding was the increase in hydrophobicity in the threads dyed only with cochineal, reaching a contact angle of 97.22°,

indicating improved water resistance. In contrast, adding mordants in treatments with cochineal and airampo decreased this property.

The durability tests revealed significant challenges for the commercial use of these products. Wash fastness was limited, with color degradation rated as severe in most treatments (values of 1 to 2 on the grayscale). However, color transfer to other fabrics during washing was minimal, with ratings ranging from 4 to 5. Regarding rub fastness, threads dyed with annatto performed exceptionally well in both dry and wet conditions. In contrast, threads treated with cochineal and mordants showed poor fastness, with values ranging from 1 to 2.

In summary, although the natural dyes evaluated provide attractive esthetic results and maintain the structural integrity of the alpaca fiber, it is essential to optimize the fixation processes to enhance color permanence. This improvement is crucial for overcoming the main technical obstacle and progressing toward sustainable commercial use in the high-value textile market.

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Data availability statement

The data presented in this study are available in the article.

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