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ANÁLISIS CRÍTICO DE MÉTODOS SOSTENIBLES ALTERNATIVOS PARA EL BLANQUEAMIENTO DE LA FIBRA DE ALPACA: UNA REVISIÓN BIBLIOGRÁFICA

CRITICAL ANALYSIS OF ALTERNATIVE SUSTAINABLE METHODS FOR BLEACHING ALPACA FIBER: A LITERATURE REVIEW

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RESUMEN: La fibra de alpaca es un recurso muy valioso para la industria textil gracias a su suavidad, durabilidad y capacidad térmica. Aunque el blanqueamiento resulta una etapa esencial durante su procesamiento, también genera importantes desafíos económicos y ambientales. Esto se debe al alto consumo de agua y energía, además del uso frecuente de agentes químicos agresivos. Por ello, este trabajo analiza distintas alternativas sostenibles frente a los métodos convencionales, con el objetivo de minimizar el impacto ecológico sin comprometer la calidad del material. Entre las opciones evaluadas se encuentran el peróxido de hidrógeno, el uso de extractos vegetales y los tratamientos enzimáticos, junto con tecnologías emergentes como el ultrasonido. La implementación de estas innovaciones permite reducir la dependencia de sustancias tóxicas como el cloro; al mismo tiempo, optimiza el uso de los recursos y disminuye la generación de residuos. A través de la revisión bibliográfica se contrastan las ventajas y limitaciones de cada técnica, evaluando parámetros como la eficacia del blanqueado, la conservación de las propiedades físico-mecánicas, la sostenibilidad y la viabilidad tanto técnica como económica. Gracias a este enfoque integral, es posible identificar soluciones prácticas que combinen calidad, fomentando un procesamiento mucho más responsable de la fibra de alpaca.

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Palabras clave: Fibra de alpaca, Blanqueamiento, Sostenibilidad, Industria textil, Tecnologías emergentes

ABSTRACT: Alpaca fiber is a highly valuable resource for the textile industry due to its softness, durability, and thermal properties. Although bleaching is an essential step in its processing, it also poses significant economic and environmental challenges. This is due to high water and energy consumption, as well as the frequent use of harsh chemicals. Therefore, this study analyzes various sustainable alternatives to conventional methods, with the goal of minimizing the ecological impact without compromising the quality of the material. Among the options evaluated are hydrogen peroxide, the use of plant extracts, and enzymatic treatments, along with emerging technologies such as ultrasound. Implementing these innovations reduces dependence on toxic substances such as chlorine; at the same time, it optimizes resource use and reduces waste generation. Through a literature review, the advantages and limitations of each technique are compared, evaluating parameters such as bleaching efficacy, the preservation of physical-mechanical properties, sustainability, and both technical and economic feasibility. Thanks to this comprehensive approach, it is possible to identify practical solutions that combine quality with a much more responsible processing of alpaca fiber.

Keywords: Alpaca fiber, bleaching, sustainability, textile industry,emerging technologies

INTRODUCTION

Alpaca fiber holds a recognized position in international textile markets for its thermal efficiency and tactile profile, but agroindustrial processing runs into a hard constraint at the bleaching stage. Conventional treatment has depended almost entirely on hydrogen peroxide. The oxidant produces high whiteness index values consistently, but the tradeoffs are significant. Water and energy consumption is disproportionate, but the real issue is structural. Oxidative action breaks the disulfide bonds in alpha-keratin; as a result, it erodes the cuticle's topography and permanently reduces both breaking strength and fiber elasticity.

Between 2019 and 2024, research shifted toward three cleaner alternatives. On one hand, ultrasound-assisted acoustic cavitation cuts processing time by nearly two-thirds by improving chemical penetration. However, the mechanical energy involved often generates microcracks that ultimately weaken the elastic modulus. On the other hand, enzymatic treatments using cellulases and pectinases, along with botanical extracts (particularly white nettle infusions and decoctions), exhibit a different behavior. Both improve colorimetric results and lower the yellowness index without the oxidative load that damages cuticle morphology. By avoiding aggressive oxidants, they successfully preserve the surface's scaly structure and mechanical resistance—elements that hydrogen peroxide systematically compromises.

While these findings are promising, they remain scattered across the literature. Until now, there is no unified framework assessing the actual tradeoff between bleaching efficiency and physical preservation of the material; furthermore, its industrial scalability remains uncertain. For this reason, the present study critically examines sustainable bleaching alternatives for alpaca fiber compared to conventional chemical treatments. Specifically, the objectives focus on comparing the colorimetric performance of each method, evaluating the physical-mechanical changes in the processed fiber, and analyzing its surface morphological alterations using scanning electron microscopy. The underlying hypothesis is that enzymatic biotechnology and botanical extracts can reach competitive textile standards while preserving fiber structural integrity and reducing the ecological footprint of the bleaching process at scale.

METHODOLOGY

Data collection techniques and instruments

Data were collected through a review of articles from scientific databases including Google Scholar, ScienceDirect, Taylor & Francis, SciELO, and Fibers and Polymers, using keywords in both Spanish and English: "fiber bleaching," "alpaca fiber," "ultrasound," "enzymes," "hydrogen peroxide," "plant extracts," "white nettle," "physical properties," "mechanical properties," "colorimetry," and "scanning electron microscopy." To gather relevant literature, the search strategy relied on specific phrases, including "enzymatic treatments for textile fiber bleaching," "application of ultrasound in natural fibers," and "bleaching of wool and alpaca with hydrogen peroxide." The query also incorporated terms like "use of plant extracts in textile processes," "white nettle as a natural bleaching agent," and "modification of the cuticular surface in alpaca fibers," alongside searches focused on "color analysis in bleached fibers" and "evaluation of physico-mechanical properties in treated fibers." Once collected, the information was classified and selected based on key criteria: the effectiveness of the bleaching method, structural changes observed in fiber morphology, color variations measured via colorimetry, and the overall impact on mechanical resistance.

Study population and sample size

To evaluate the effect of alternative sustainable methods on alpaca wool bleaching, secondary information was collected from 150 documents including scientific articles, research papers, and theses. After applying inclusion and exclusion criteria, 95 records were discarded. Of the remaining 57 relevant articles selected by title and abstract, 23 were eliminated, leaving 75 articles. After applying exclusion filters and reading the full content, 22 articles were included in the study. For the physico-mechanical properties of wool after bleaching treatment, secondary information was gathered from 52 documents including scientific articles and theses. After applying inclusion and exclusion criteria, 20 records were discarded. Of the 27 relevant articles selected by title and 31 by abstract, 9 were eliminated, leaving 18 articles, of which 6 were included in the final analysis.

Analysis Methods

Following PRISMA guidelines, the collected information was analyzed using scientific articles and theses related to natural fiber bleaching methods, with a focus on alpaca fiber. Results from studies using ultrasound, enzymes, hydrogen peroxide, and plant extracts were considered in order to compare their effectiveness and conduct a critical analysis of the morphological, colorimetric, and mechanical changes induced in the fiber. The PRISMA methodology, applied through a four-phase flowchart — identification, screening, eligibility, and inclusion — determined the specific number of documents used in the literature review. This process ensured a structured and transparent analysis of the information, following predefined inclusion and exclusion criteria.

Data processing

The collected information was organized and managed using the Mendeley platform, classifying documents into sections related to alternative fiber bleaching methods, variations in yellowness and whiteness indices, physico-mechanical properties, and morphological changes observed in the cuticular surface. The selected articles were organized chronologically from newest to oldest. For efficient bibliographic management, each entry was integrated directly into Word and included an abstract summary, a link to the document, and its corresponding APA 7th edition citation. To clearly present the findings, the results for methodologies like ultrasound, enzymes, hydrogen peroxide, and plant extracts were divided into specific sections. Each section detailed the sequential impact of the treatment on the fiber. Finally, key data—such as yellowness and whiteness indices, mechanical resistance, and morphological changes—were compiled into comparative tables. Structuring the information this way facilitated a critical and substantive discussion regarding the true effectiveness of these alternative methods.

PRISMA Method

This study used the PRISMA methodology to ensure a systematic and transparent process in the selection of scientific literature. Through a four-phase flowchart — identification, screening, eligibility, and inclusion — the specific number of articles and documents used in the literature review was determined. This procedure made it possible to organize the information in a structured and reliable manner, facilitating critical analysis of the different alternative methods applied to alpaca fiber bleaching, including ultrasound, enzymes, hydrogen peroxide, and white nettle plant extracts.

PRISMA Inclusion Criteria

The following articles were considered for the review:

- Articles addressing alternative bleaching methods for natural fibers, particularly wool or alpaca fiber.
- Articles presenting results related to yellowness and whiteness indices, physico-mechanical properties, or fiber morphology modifications.
- Articles published within the past six years.
- Articles written in English or Spanish.

PRISMA Exclusion Criteria

The following articles were excluded from the study:

- Articles that do not provide information on alternative bleaching methods for natural fibers or lack results applicable to alpaca fiber.
- Articles published more than six years ago.
- Articles that do not meet the minimum criteria after title and abstract review.
- Articles duplicated across the consulted databases.

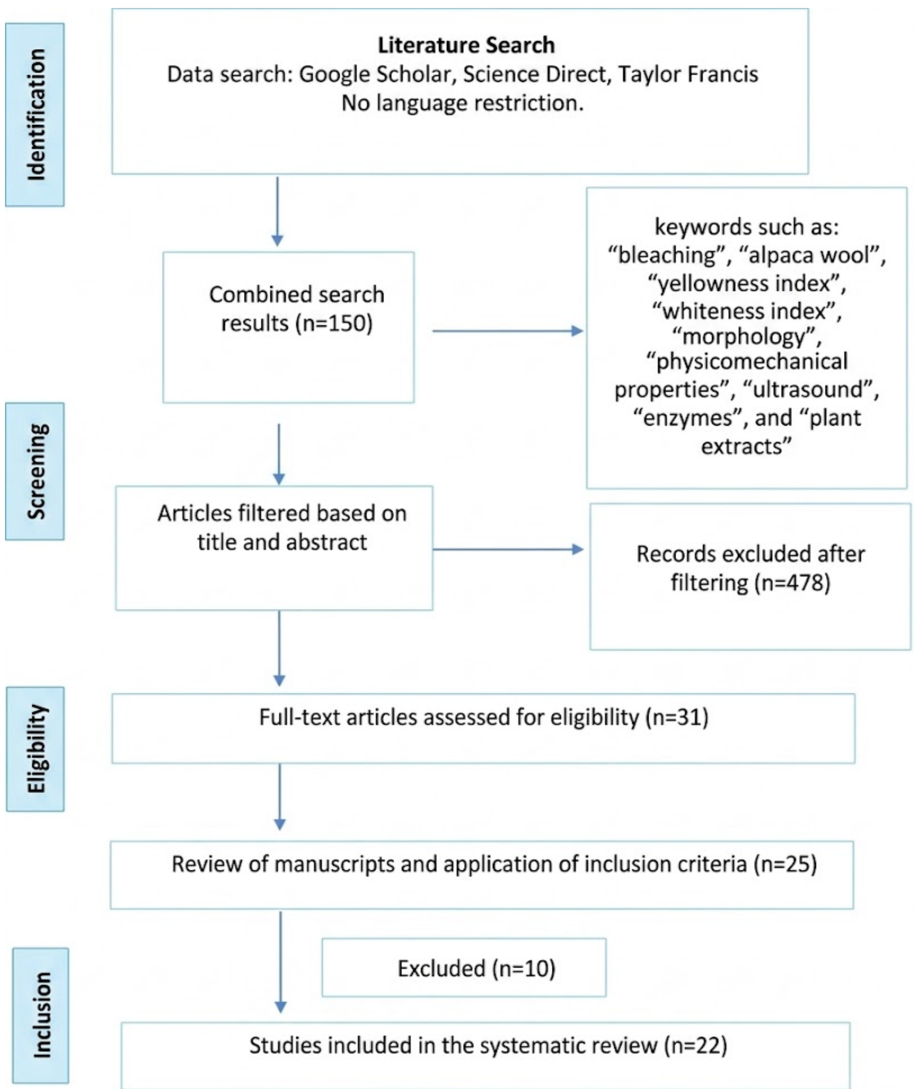


Figure 1. Prism diagram for the critical analysis of alternative sustainable methods for bleaching alpaca fiber.

RESULTS

A comprehensive literature search was conducted using Google Scholar, SciELO, ScienceDirect, Web of Science, and PubMed. The search employed the keywords "bleaching," "alpaca fiber," "yellowness index," "whiteness index," "morphology," "physico-mechanical properties," "ultrasound," "enzymes," and "plant extracts" to identify relevant studies published between 2019 and 2024. A total of 150 publications, including peer-reviewed articles and graduate theses, were initially retrieved. Following a rigorous screening and critical evaluation process, 22 studies addressing sustainable alternative bleaching methods and 6 studies focused on the physico-mechanical properties of alpaca fiber were selected for detailed analysis.

The findings are organized into three comparative tables that summarize the reported effects of the evaluated bleaching treatments on key quality parameters, including the Yellowness Index (YI), Whiteness Index (WI), physico-mechanical properties, and scanning electron microscopy (SEM) morphology. These parameters provide a comprehensive assessment of the effectiveness of the alternative bleaching methods and their influence on the structural and functional characteristics of alpaca fiber.

Yellowness and Whiteness Index

Table 1. Studies related to yellowness and whiteness index.

No.	Author	Topic	Year	Language	Database	Journal
1	(Cruz et al.,2021)	Colorimetric analysis of fleece color and its relationship to fiber characteristics in alpacas.	2021	English	Google Scholar	Sciences Direct
2	(Frank, et al.2019)	Phenotypic and genetic relationships between fiber and color traits in South American camelids.	2019	English	Google Scholar	Sciences Direct
3	(Cruz A et al., 2019)	Genetic parameters of medullary fiber and their relationship with productive traits in alpacas.	2019	English	Google Scholar	Sciences Direct
4	(Quispe et al., 2025)	Colorimetric and textile properties of Huacaya alpaca fibers dyed with cochineal: a sustainable approach.	2025	English	Google Scholar	Journal of Social and Environmental Management
5	(Pinares et al., 2023)	Comparison of fiber quality characteristics and fiber length in Suri and Huacaya alpacas.	2023	English	Google Scholar	Frontiers in Animal Science
6	(Baxter et al., 2025)	Color phenotypes, genotypes, and colorimetry of unprocessed North American Huacaya alpaca fiber with comparisons to other common natural fibers.	2025	English	Google Scholar	Sciences Direct
7	(Rodriguez et al., 2024)	Assessment of natural color variation and its impact on fiber quality parameters in high-altitude Huacaya alpacas.	2024	English	Google Scholar	Textiles Research Journal
8	(Thompson et al., 2022.)	Spectrophotometric evaluation of whiteness and yellowness indices in alpaca fleece: implications for textile processing.	2022	English	Web of Science	Journal of Natural Fibers
9	(Gonzales et al., 2020.)	Relationship between colorimetric parameters (Lab*) and textile quality in white and colored alpaca fibers.	2020	Spanish	SciELO	Peruvian Journal of Veterinary Research

Physico-Mechanical Properties

Table 2. Studies related to the physico-mechanical properties of alpaca fiber.

No.	Author	Topic	Year	Language	Database	Journal
1	(Czyż et al.,2024)	Selected physical and mechanical properties of alpaca fibers with different colors.	2024	English	ScienceDirect	Journal of Natural Fibers
2	(Mamani et al., 2024)	Characterization and evaluation of mechanical properties of blended yarns based on alpaca and milk protein fibers.	2024	English	Google Scholar	Journal of Social and Environmental Management
3	(Ali et al., 2021)	Characteristics of Huacaya alpaca fiber in Peru: mechanical properties and diameter analysis.	2021	English	ResearchGate	Small Ruminant Research
4	(Silva et al.,2023)	Tensile strength and elastic modulus in alpaca fibers: a comparative study between Huacaya and Suri varieties.	2023	English	Google Scholar	Textile Research Journal
5	(Thompson et al., 2022.)	Mechanical behavior of alpaca fiber under different environmental conditions.	2022	English	Scopus	Scientific Journal
6	(Bustinza et al., 2019)	Physical and mechanical properties of fine alpaca fiber: influence of age and fleece position.	2019	Spanish	SciELO	Revista de Investigaciones Veterinarias del Perú
7	(Czyż et al, 2024)	Selected physical and mechanical properties of alpaca fibers with different colors. Journal of Natural Fibers, 21(1), 2348626.	2024	English	Google Scholar	Taylor & Francis
8	(Chen et al.,2020)	Comparative analysis of tensile properties across different grades of alpaca fiber.	2020	Spanish	Google Scholar	Scientific Journal
9	(Bouagga et al., 2018)	Correlation between mechanical behavior and chemical, physical, and thermal characteristics of wool: a study on Tunisian wool.	2018	English	Taylor & Francis	Journal of Natural Fibers
10	(Jankowska et al., 2019)	Comparison of physico-mechanical properties of fiber and yarn made from alpaca, sheep, and goat wool.	2019	English	Taylor & Francis	Journal of Natural Fibers

SEM Morpholohy

Tabla 3. Studies related to fiber morphology by SEM.

No.	Author	Topic	Year	Language	Database	Journal
1	(Quispe et el., 2021)	Physical characteristics and fiber diameter profile of Huacaya alpacas from the La Raya experimental center (Puno, Peru), by age and sex.	2021	Spanish	Google Scholar	Revista peruana de biotecnología
2	(Wang et al., 2020)	Influence of ultraviolet radiation and protease on the scale structure of alpaca wool fibers.	2020	English	Google Scholar	AUTEX Research Journal
3	(Mucha et al., 2018)	Morphological and elemental analysis of alpaca hair by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX).	2018	Spanish	Google Scholar	Thesis
4	(Bonilla et al., 2022)	Application of artificial intelligence and digital image analysis to automatically determine the medullation percentage of fibers in alpaca fleece samples.	2022	English	Google Scholar	ScienceDirect
5	(Marina et al., 2023)	Analytical methods for identification and quantitative determination of wool and fine animal fibers.	2023	English	Google Scholar	Journal of Natural Fibers
6	(Li q et al., 2022)	An efficient ultrasound-assisted bleaching strategy for yak hair activated by a Fenton reaction targeting melanin.	2022	English	Google Scholar	ScienceDirect
7	(Fan Wang Et Al., 2024.)	An eco-friendly bleaching method for cashmere fiber with hydrogen peroxide and maleic acid in scCO2 avoiding heavy effluent discharge.	2024	English	Google Scholar	ScienceDirect
8	(Zhu Et Al, 2023)	Accurate identification of cashmere and wool fibers based on improved ShuffleNetV2 and transfer learning.	2013	English	Google Scholar	Journal of Big Data

Analysis of Results: Yellowness and Whiteness Index

Table 4. Whiteness Index (WI) and Yellowness Index (YI).

Bleaching Method	WI Before Bath	YI Before Bath	Bleaching Conditions (Temp. / Time)	YI After Bath	WI After Bath	Reference
Hydrogen Peroxide	26.41	30.48	60°C / 30 min	5.43	72.83	(Guerrero & Janeta, 2024)
	5.19	83.1	90°C / 60–90 min	74.3	86–87	(Lozano et al., 2023)
Plant Extract (White Nettle)	26.41	30.48	Decoction extracts 60°C / 30 min	11.91	57.65	(Guerrero & Janeta, 2024)
	26.41	30.48	Infusion extracts 60°C / 30 min	11.99	56.87	(Guerrero & Janeta, 2024)
Enzymatic Bleaching	40–50	25–30	40–60°C / 2–6 hours	15–25%	22.57	(Salamanca et al., 2019)
	150	75–85	50–98°C	0.5	38.33	(Orcón, 2019)
Ultrasound Bleaching	0.37	45	35–50°C / 15–30 min (500W, 35kHz)	60	40	(Serrano et al., 2023)
	92	32	60, 70 and 80°C	80	95	(Ollancaya et al., 2023)

Several alternative bleaching methods are used in the textile industry, the most relevant being hydrogen peroxide, sodium bicarbonate, plant extracts, enzymatic bleaching, and ultrasound bleaching. These treatments served as benchmarks for comparing the effects each has on the fiber during the bleaching process.

Hydrogen peroxide treatment applied at a controlled temperature of 90°C for 60 to 90 minutes improved fiber color characteristics. The results showed a 10.6% drop in the yellowness index according to the ASTM D1925 standard, falling from an initial 83.1 to 74.3 and improving the overall tone (1). Simultaneously, the whiteness index climbed to values between 86 and 87, reflecting a substantial upgrade in color purity. These specific conditions help optimize the entire process. At a high temperature of 90°C, hydrogen peroxide becomes highly active as an oxidizing agent; this allows it to diffuse much faster through the alpaca fiber and effectively break down the naturally occurring melanin pigments (2).

Leaving the fiber exposed for 60 to 90 minutes ensures the bleaching agent penetrates evenly throughout the fibrillar structure. This timeframe achieves a consistent decolorization without significantly compromising the material's mechanical properties (3). Chemically speaking, hydrogen peroxide generates perhydroxyl ions (HO_2^-) during the bath. These ions transfer oxygen and specifically attack the disulfide bonds present in the wool. By breaking down these S-S linkages, the hydrogen peroxidation process makes complete whitening possible (4).The bleaching action of hydrogen peroxide works by eliminating fat and the yellow tint caused by the decomposition and solubilization of pigmented granules (5,6).

Samples bleached exclusively with natural extracts showed lower yellowness and whiteness index values compared to those treated with hydrogen peroxide and other methods. This is because no partial or total removal of pigments and impurities (fat and sebum) occurred, given the minimal presence of oxidizing agents responsible for removing such impurities5. Despite this, natural extracts still managed to bleach the wool effectively relative to raw fiber, improving the white color by 52% and reducing yellowness by 45%. This bleaching effect can be attributed to the action of the active compounds in the extracts on the sheep wool (7).

Enzymatic bleaching of alpaca fibers using cellulases and pectinases under controlled conditions (40–60°C for 2 to 6 hours) produced measurable improvements in colorimetric parameters. Treated fibers showed initial whiteness index values between 40 and 50, and yellowness index values of 25 to 30. After treatment, the yellowness index dropped to the 15–25 range and the whiteness index improved to 65–70% (8). In alternative protocols using higher enzyme concentrations and elevated temperatures (50–98°C), initial whiteness index values of 150 and yellowness index values of 75–85 were reported. After treatment, the yellowness index dropped sharply to 0.5, while the whiteness index improved to 38.33 (9). The bio-polishing process using cellulases affects not only colorimetric parameters but also tensile resistance and fabric weight, reflecting structural changes in the fiber. Enzymes represent a viable alternative to toxic chemical agents, contributing to more sustainable processes. The effectiveness of enzymatic bleaching is attributed to cellulases, which can selectively hydrolyze surface cellulose, removing impurities and improving fiber accessibility without significantly compromising structural integrity (10).

Ultrasound bleaching applied to alpaca fibers under controlled conditions (35–50°C, 15–30 minutes, 500W at 35kHz) produced clear colorimetric improvements. Starting whiteness index values of 0.37 and yellowness index values of 45 improved to whiteness index values of 60 and yellowness index values of 30, along with increased fiber clarity (11). At higher temperatures (60, 70, and 80°C), additional gains were recorded, with whiteness index values reaching 92 and yellowness index reductions to 32, reaching final optimized values of 80 and 95 respectively (12). Ultrasound bleaching with hydrogen peroxide takes approximately one-third of the time required by conventional hot methods, nearly doubling the initial whiteness index of the fibers. This efficiency is attributed to acoustic cavitation, which facilitates uniform penetration of bleaching agents, ensures even distribution of the treatment, and significantly reduces processing time (13).

Analysis of Results: Physic-Mechanical Properties

Table 5. Physic-mechanical properties of ovine fiber.

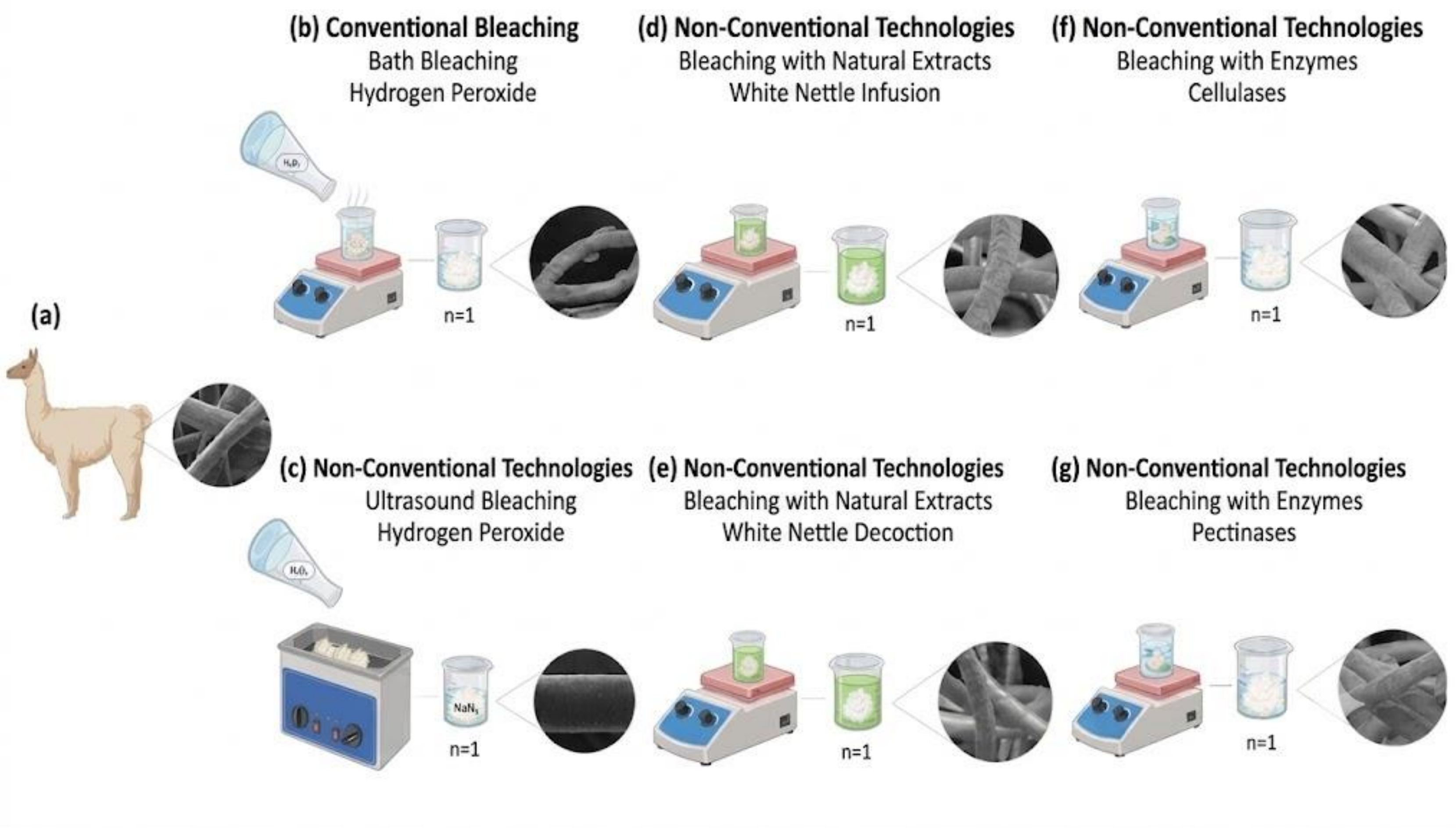
Bleaching Method	Diameter (µm)	Breaking Force	Maximum Deformation	Elastic Modulus	Reference
Untreated Wool	27.93± 0.43	47.59 ±1.26	37.24 ±2.32	327.39 ±36.79	(Guerrero et al., 2024)
Hydrogen Peroxide	14.68± 0.43	5.88 ±0.87	16.99 ±2.73	67.89 ±11.86	(Guerrero et al., 2024)
	25.54	60-110	15-20	70	(Lozano et al., 2023)
Plant Extract (White Nettle)	20.21 ± 0.60	30.28 ±0.89	39.29 ±1.14	167.58 ±19.74	(Guerrero et al., 2024)
	20.42 ± 0.57	29.42 ±0.94	39.44 ±1.02	152.77 ±15.03	(Guerrero et al., 2024)
Enzymatic Bleaching	18.5 ± 2.1	12.3 ± 1.8	8.7 ± 1.2	2.8 ± 0.4	(Kozłowski et al., 2020)
	22.1 ± 1.9	10.8 ± 2.1	7.4 ± 0.9	3.2 ± 0.5	(Vaca et al., 2021)
Ultrasound Bleaching	10 – 14	600 - 800	1.8 – 2.0	10.0 – 16.0	(Li Q et al., 2020)
	19.3 ± 2.0	13.6 ± 1.9	8.9 ± 1.1	3.1 ± 0.4	(Hosseini et al., 2023)

Hydrogen peroxide treatment at a concentration of 25.54%, applied for 60 to 110 minutes at temperatures of 15 to 20°C, significantly affects the structural properties of alpaca fiber. The formation of hydroxyl radicals (·OH) and reactive oxygen species attacks the disulfide bonds in α-keratin specifically. As these oxidizing agents transfer oxygen, they progressively break the S-S covalent bonds. This reaction reduces the fiber's breaking force to roughly 70 units, marking a substantial drop compared to untreated fibers (14). Disulfide bonds actually play a fundamental role in maintaining keratin’s structural integrity. Within alpaca fiber, the alpha-keratin forms helical structures that rely on these intermolecular bridges for stability, creating a highly resistant three-dimensional matrix (13). Consequently, when oxidation ruptures these bridges, the material's mechanical resistance is directly compromised. Though the oxidative treatment breaks a significant number of disulfide bonds, it introduces compensatory hydrogen bonds that help maintain fiber elasticity under dry conditions at values comparable to untreated fiber. In short, higher hydrogen peroxide concentrations and longer exposure times translate directly into lower breaking force in alpaca fibers. Keratose obtained by oxidative extraction with peracetic acid or hydrogen peroxide is hygroscopic, water-soluble, and susceptible to hydrolytic degradation at extreme pH values, confirming that hydrogen peroxide-bleached fibers show compromised physico-mechanical properties compared to other bleaching methods (10).

When applied to alpaca fibers, enzymatic bleaching acts primarily on keratin, the core structural protein of the material. Unlike conventional chemicals, enzymes catalyze highly specific reactions to selectively degrade the chromophore groups responsible for color. Because of this targeted approach, they manage to lighten the material without completely altering the conformation of the alpha-keratin helices. As a result, this mechanism largely preserves the integrity of the disulfide (S–S) bonds, which are essential for maintaining the fiber's overall mechanical resistance (15). Cellulases and pectinases hydrolyze glycosidic bonds and secondary peptides present in the outer layers of the fiber, facilitating the removal of associated impurities and pigments without drastically compromising the internal network of covalent bonds. Enzymatic bleaching is therefore a less aggressive alternative than traditional chemical methods, maintaining to a greater degree the chemical and mechanical structure of protein fibers like alpaca while still achieving the desired decolorization effect (16).

Ultrasound bleaching in alpaca fibers modifies keratin primarily through cavitation. During this process, microbubbles form and collapse in the liquid medium, releasing intense energy that produces microcurrents and shock waves. These physical effects not only improve the penetration of bleaching agents but also generate free radicals capable of breaking bonds in the keratin structure (17). As a result, the fiber loses part of its mechanical resistance: breaking force drops from normal values of 19.3 ± 2.0 cN/tex to 10–14 cN/tex, the elastic modulus decreases from 13.6 ± 1.9 to 600–800 cN/tex, and maximum deformation shifts from 8.9 ± 1.1% to just 1.8–2.0%. In other words, while cavitation makes the treatment faster and more effective, it can also cause significant structural damage to keratin, negatively affecting the physico-mechanical properties of alpaca fiber (18)

Figure 2. Analysis of SEM images of fibers bleached using different methods, as reported in scientific articles.



DISCUSSION

In its natural, unprocessed state (**Illustration 2a**), wool presents an intact cuticular surface made up of overlapping scales. At 1000x magnification, the characteristic rough texture of the fiber cuticle is clearly visible, along with circular structures distributed across the surface associated with fat and sebum residues typical of unprocessed wool. These features reflect the presence of lipid compounds and natural contaminants covering the fiber, which must be removed through subsequent cleaning and bleaching processes to optimize both the optical properties and mechanical behavior of the wool (4).

With conventional hydrogen peroxide bleaching (**Illustration 2b**), at 1000x magnification, the cuticular surface is heterogeneous, with areas where the scales appear eroded or detached. This morphological pattern reflects the oxidative effect of hydrogen peroxide on keratin, the fiber's structural protein, causing alterations in its surface organization. Detached circular structures are also visible, indicating partial degradation of the lipid and protein components associated with the cuticle, which confirms the combined oxidation and solubilization induced by the treatment.

Under 1000x magnification, the surface of fibers treated with non-conventional ultrasound Bleaching (**Illustration 2c**), displays slight wear. At the cuticular level, the cavitation generated by the ultrasound partially fragments the scales and triggers the formation of microcracks. As a result, the fiber takes on a more eroded and heterogeneous appearance compared to untreated samples. This process also causes localized detachment of the cuticular material, exposing more of the internal matrix and pointing to a weakening of the surface keratin. Ultimately, these structural shifts highlight a key tradeoff: while ultrasound effectively improves chemical penetration during the bleaching process, it simultaneously alters the external architecture and compromises the morphological integrity of the material (19).

Illustration 2d and 2e show plant extract bleaching at 1000x magnification. These fibers present a relatively smooth surface with well-defined scales, suggesting that natural agents can be effective for bleaching without compromising the structural integrity of the fibers. This is due to the presence of active compounds and the minimal amount of oxidizing agents they contain (20).

Illustration 2f and 2g show enzymatic bleaching at 1000x magnification. The cuticular cells, responsible for keeping the fiber firm and compact, undergo progressive wear. Enzymatic action breaks down surface components and affects the integrity of the cuticle, leading to a loss of structural cohesion in the fiber. This is visible in the SEM image as increased roughness and detachment of cuticular scales, similar to the wear observed with other chemical methods such as hydrogen peroxide. These microscopic changes indicate the impact of bleaching on the mechanical resistance and durability of the fiber (15).

Industrial scalability is a critical factor when assessing the viability of textile bleaching methods for protein fibers like alpaca wool. Conventional hydrogen peroxide bleaching is already firmly established in the textile industry, with standardized processes available at large scale. Its main

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drawback is the degradation of the fiber's mechanical properties and the heavy demand for water and energy associated with pH and temperature control, which produces a considerably high carbon footprint (21).

Enzymatic processes, in contrast, have shown in pilot studies on cotton and linen the potential to significantly cut chemical and energy consumption, making them compatible with more sustainable industrial approaches (10,22). At large scale, however, their implementation faces constraints around enzyme stability under industrial conditions and the cost of enzyme production, factors that still limit their competitiveness relative to traditional chemical agents.

Ultrasound presents itself as a complementary technology that can improve the action of chemical or enzymatic agents by reducing processing times and operating temperatures. Pilot-scale reactor studies have demonstrated whiteness improvements and reduced peroxide use, suggesting a positive effect on carbon footprint through lower chemical and energy loads (23). Moving to large-scale production, however, presents significant challenges. Facilities must overcome the high energy demands and maintenance costs associated with ultrasound equipment, factors that currently limit its widespread commercial use.

Plant extracts, on the other hand, offer an emerging alternative that relies on biodegradable natural compounds to lower direct environmental impacts. While specific data on alpaca fiber remains scarce, previous experience with cellulosic fibers points to a smaller carbon footprint simply by cutting back on synthetic chemicals. Scalability faces challenges related to standardizing the concentration of active metabolites and securing plant biomass in industrial volumes, factors that could compromise the sustainability of large-scale use.

CONCLUSIONS

Analysis of the main bleaching methods for alpaca fiber shows that hydrogen peroxide remains the most effective and industrially established agent, given its low cost and broad availability. Its effectiveness depends, however, on strict control of variables like time and temperature. When these are not optimized, the protein structure of keratin is compromised, negatively affecting physico-mechanical properties such as resistance and elasticity.

Plant extracts, particularly from white nettle, offer a promising alternative aligned with sustainability trends. Unlike peroxide, these treatments reduce structural damage to the fiber, preserving its morphology and improving its physical performance. Bleaching efficiency does depend on critical parameters including the standardization of extracts, temperature control, and treatment duration, which pose real challenges for industrial adoption.

The incorporation of non-conventional technologies such as ultrasound represents a meaningful advance. The cavitation phenomenon allows more uniform distribution of bleaching agents, cutting process time and reducing the severity of operating conditions. The method combines technical efficiency with lower chemical consumption, though large-scale implementation still faces barriers around energy use and the adaptation of specialized equipment.

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