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A Brief Overview of the Chemistry of Leather Tanning and Current Trends: Applications of Tanned Leathers

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ABSTRACT
This paper aimed at providing a detailed overview of leather and chemistry of tanning, discussing the underlying chemical reactions used to convert collagen-rich raw hides into durable and purposeful leather products. The paper also delves into evolving trends in leather tanning processes and also highlights the general applications of tanned leathers with a view to understand their significance. It begins by exploring the structural composition of animal skin, particularly the central role of collagen in tanning. Besides, it compares the major tanning methods including chrome, vegetable, aldehyde, and synthetic tanning based on their chemical mechanisms, efficiency, environmental impact, and influence on leather properties. This overview also explores emerging trends such as enzyme-assisted tanning, bio-tanning, and the use of nanomaterials to enhance leather performance while minimizing environmental damage. Moreover, it discusses the roles of fat liquoring, dyeing, and finishing processes in determining leather texture, flexibility, and appearance. The method used to conduct this overview involved a systematic review of 70 relevant peer-reviewed articles published in online databases comprising Google Scholar, MDPI, and Scopus from 2011 to 2024. The study found that despite the environmental challenges of chromium tanning, it remains dominant due to its ability to produce soft and heat-resistant leather. Conversely, vegetable and aldehyde tanning offer biodegradable and harmless alternatives, with expanding applications in fashion, footwear, biomedical industries, and upholstery. By critically comparing diverse tanning methods for their mechanisms, efficiencies, and environmental impacts, the overview highlights the shift toward sustainable, high-performance leathers while retaining attention to practical finishing processes like fat liquoring and dyeing. Finally, this research concludes by emphasizing that the future of leather tanning lies in integrating advanced materials science with green practices to support high-performance and eco-friendly leather production.

Keywords:
Leather tanning, Chemistry, Classification, Properties and structure, Applications

INTRODUCTION

The art and science of tanning, which involves the conversion of animal hides and skins into durable and usable leather, has a long and rich history that spans thousands of years. Initially developed as a means to prevent hides from decomposing and to make them more flexible for practical use, tanning has undergone significant transformations driven by cultural, technological, and scientific advancements (Thanikaivelan *et al.*, 2015). The earliest known tanning processes date back to prehistoric times, when people used natural materials like tree bark, leaves, and animal fats to preserve animal skins. Over the centuries, tanning techniques evolved from purely empirical practices to sophisticated industrial processes, reflecting humanity's ongoing quest to improve leather quality, production efficiency, and sustainability (Covington, 2017). By the Middle Ages, vegetable tanning, which employs tannins derived from plant sources, had become widespread in Europe. However, it was not until the 19th century, with the advent of chromium salts and other chemical tanning agents, that the industry saw a revolutionary shift in leather production (Kanth & Madhan, 2019).

This overview therefore seeks to ask this research question: How can a detailed understanding of the chemical mechanisms underlying traditional tanning processes inform and accelerate the development of eco-friendly and high-performance alternatives such as enzyme-assisted, bio-, and nanomaterial-based tanning?

The scope covers the chemistry and technology of leather tanning from both a fundamental and contemporary perspective. It examines the structural composition of animal hides, the chemical transformations of collagen during tanning, and the comparative mechanisms of major tanning methods such as chrome, vegetable, aldehyde, and synthetic processes. The overview is limited to peer-reviewed publications and reputable database sources (2011–2024), focusing on chemical principles, process efficiencies, environmental impacts, and end-use performance, without undertaking experimental work or market-economic evaluations.

The novelty of this research lies in its comprehensive synthesis of both the fundamental chemistry and the latest technological advances in leather tanning, presented through a systematic review of recent literature. While most conventional reviews focus mainly on traditional chrome or vegetable tanning (El-Molla *et al.,* 2012; Dutta, 2024), this brief overview uniquely integrates an in-depth chemical analysis of collagen transformations with emerging eco-friendly trends such as enzyme-assisted, bio-, and nanomaterial-based tanning. Furthermore, existing literature treats conventional methods or new technologies separately (Covington, 2018; Fang & Li, 2019), while this study critically bridges the two to inform both scientific research and industrial practice

REVIEW METHODS

A thorough literature search was conducted using online databases, including Google Scholar, MDPI, and Scopus, to collect relevant articles on the chemistry of leather and tanning. Various search terms were utilized to cover the wide-ranging aspects of leather chemistry and tanning processes, including Leather Chemistry, Tanning Agents, Vegetable Tanning, Chrome Tanning, Leather Processing, Sustainable Tanning, Collagen Structure, Leather Properties, Leather Dyeing, Fatliquoring, and Leather Finishing. This search approach yielded approximately seventy peer-reviewed articles published from 2011 to 2024, which were further categorized based on their relevance to the topic of this research.

The selection criteria focused on articles that addressed key areas of leather chemistry, including the structure and properties of raw hides, mechanisms of tanning, types and classification of tanning agents, the chemical basis for leather properties, and modern sustainable tanning techniques. The literature was categorized into different thematic areas to provide a comprehensive overview of the subject. These themes included the historical evolution of tanning methods, mechanisms underlying various tanning processes, environmental implications of tanning, technological innovations in leather processing, and emerging sustainable practices.

The geographical scope of this overview is broad, encompassing studies from various regions such as Africa (e.g., Nigeria, Egypt, and Ethiopia), Asia (e.g., India, China, and Pakistan), Europe (e.g., Italy, United Kingdom, and Germany), and North America (e.g., United States and Canada). The diverse geographical representation ensures that different perspectives on tanning practices and the leather industry are considered, reflecting the global nature of leather production and processing.

The selected articles served as the foundation for this comprehensive overview, providing insights into current trends, challenges, and advancements in the field of leather chemistry. The overview also includes discussions on the historical context and recent technological advancements in tanning, considering factors such as environmental impact, sustainability, and economic relevance to create a well-rounded analysis.

Method of Synthesis

This overview employed a systematic literature reviewto **i**ntegrate and analyze current knowledge on the chemistry of leather tanning and its evolving applications. Relevant peer-reviewed articles published between 2011 and 2024 were retrieved from databases such as Google Scholar, MDPI, and Scopus, yielding a total of about 70 studies that met predefined inclusion criteria. The selected works were critically examined and thematically organized to compare traditional tanning methods-chrome, vegetable, aldehyde, and synthetic-while highlighting their chemical mechanisms, efficiencies, and environmental impacts. Emerging innovations, including enzyme-assisted, bio-tanning, and nanomaterial-based processes, were similarly evaluated. This structured, comparative synthesis provides an evidence-based framework that links fundamental collagen chemistry with contemporary, eco-friendly practices, ensuring a comprehensive and balanced assessment for the manuscript.

Historical Evolution of Tanning Methods

The historical development of tanning can be broadly categorized into three major phases: ancient, traditional, and modern. In ancient times, early humans utilized rudimentary tanning methods involving the application of animal fats, brains, and smoke to raw hides, which imparted some degree of preservation (Thanikaivelan *et al.*, 2015).This method, known as brain tanning, is still practiced in some indigenous cultures today, though on a smaller scale. By contrast, the traditional phase, which began around 5,000 years ago, introduced vegetable tanning, where tannins from plant sources such as oak and chestnut bark were used to stabilize hides (Das *et al.,* 2015). This practice was more systematic and produced leather with improved durability and resistance to water. In fact, archaeological findings suggest that the ancient Egyptians and Romans employed sophisticated vegetable tanning techniques, evidenced by well-preserved leather artifacts found in tombs and historical sites (Buljan & Kral, 2021).

The modern phase of tanning commenced in the late 19th century with the introduction of chemical tanning agents, most notably chromium salts. Chromium tanning rapidly gained popularity due to its ability to produce leathers with superior strength, softness, and water resistance in a significantly shorter time compared to traditional vegetable tanning (Thanikaivelan *et al.,* 2015). This shift also facilitated the mass production of leather, transforming it from a handcrafted commodity to an industrial product. By the mid-20th century, other tanning agents, including synthetic and mineral-based chemicals, began to emerge, further diversifying the leather industry (Patel & Sharma, 2018). Despite these advancements, the environmental impact of chemical tanning, particularly the disposal of chromium-containing wastes, has remained a critical issue. As a result, recent developments in tanning have focused on sustainability, including the use of eco-friendly tanning agents and processes that minimize environmental harm (Meng & Liu, 2020).

Biology of Animal Skin

Animal skin has three layers: the top epidermis layer, the hypodermis layer inside the body, and, in between, the dermis layer. There is a slight variation in the dermal layer, animal to animal and between breeds in terms of epithelium thickness of sweat glands; otherwise, all animal skin has three dermal layers. The outermost layer, the epidermis, consists mainly of keratinocytes, melanocytes, Langerhans cells, Merkel cells, and sensory nerves protecting the skin from damage caused by the surrounding environment. The epidermis layer consists of five sub-layers that work together to continually rebuild the surface of the skin. The dermis layer, located just under the epidermis layer, has blood vessels, lymph vessels, hair follicles, sweat glands, sebaceous glands, and nerve endings (Thanikaivelan *et al.*, 2015). The dermis is held together by fibrous collagen protein fibers. The dermis layer is much thicker than the other two layers and works as a thermoregulator (Patel & Sharma, 2018). The dermis layer consists of two sub-layers: the papillary layer, which is composed of thin collagen fibres, and the reticular layer, consisting of thick collagen fiber. The innermost hypodermis or subcutaneous layer consists of a network of fat and collagen cells. Its function includes protecting the inner organs, storing fat as an energy reserve, and working as a heat insulator. The difference in morphological features of cow and buffalo's skin was documented by Mota-Rojas *et al.* (2021) asshown in a schematic diagram in Fig. 1.

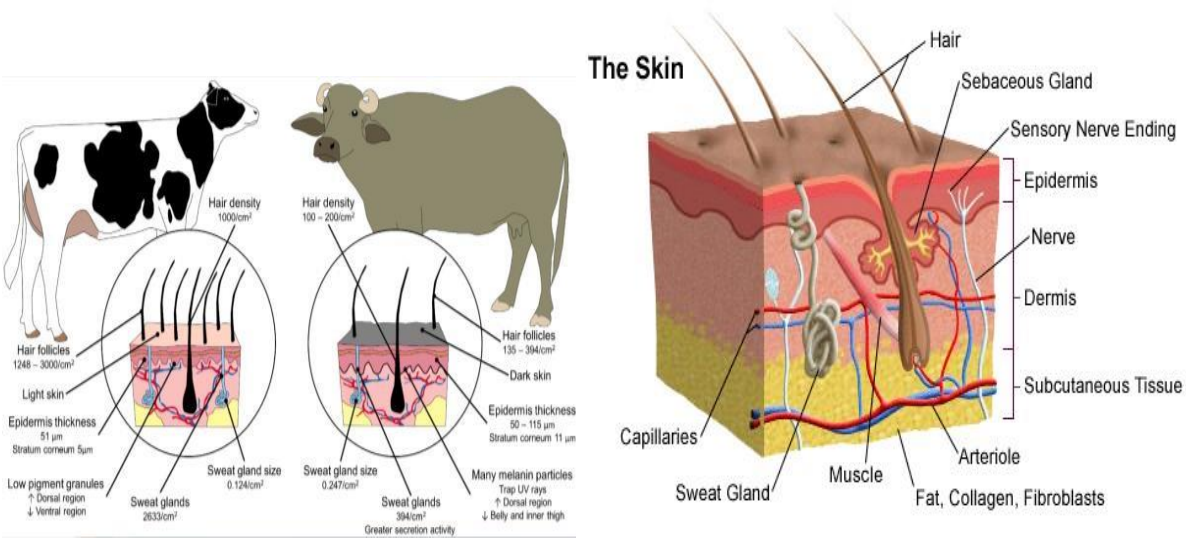


Fig. 1: Difference in skin characteristics between cattle and buffaloes (Mota-Rojas *et al.,* 2021)

The Chemistry Underlying Tanning Processes

The fundamental goal of tanning is to convert the protein structure of raw hides, primarily composed of collagen, into a chemically stable and durable material. Collagen, a fibrous protein, is prone to degradation by microorganisms and environmental factors in its natural state (Patel & Sharma, 2018). Tanning modifies the collagen structure through chemical reactions that stabilize its fibers, making them resistant to decay and imparting desirable mechanical properties (Rajamani & Rao, 2017). The process typically involves three main stages: pre-tanning, tanning, and post-tanning. Pre-tanning treatments remove unwanted components, such as hair and fats, while the actual tanning phase introduces chemicals that cross-link collagen fibers. Post-tanning processes further enhance the leather's characteristics through dyeing, fat liquoring, and finishing operations (Kanth & Madhan, 2019). China *et al.* (2020) reported the collagen triplet structure of raw skin as shown in Fig. 2.

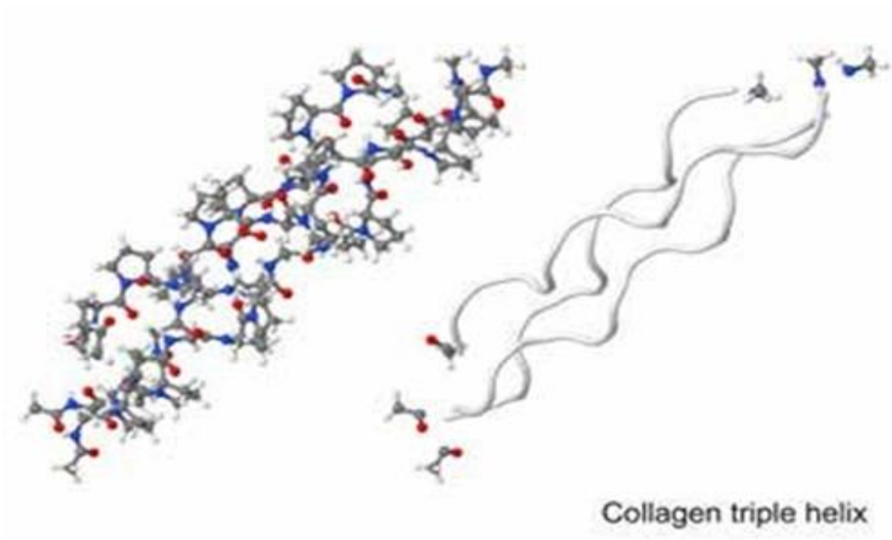


Fig. 2: Collagen triplet structure of raw skin (China *et al*., 2020)

Modern Classification of Tanning Methods

Today, tanning methods are classified based on the type of tanning agents used, which include mineral, vegetable, synthetic, and alternative eco-friendly agents. Chromium tanning remains the most widely practiced method, accounting for about 80% of global leather production. It involves the use of trivalent chromium salts, which penetrate the collagen matrix and form stable cross-links, resulting in leather with excellent physical properties (Thanikaivelan *et al.,* 2015). However, due to environmental concerns associated with chromium waste, alternatives like vegetable tanning and chrome-free tanning have gained traction (Sundar *et al.,* 2016). Vegetable tanning uses polyphenolic compounds from plant sources, which interact with collagen through hydrogen bonding and hydrophobic interactions, producing leather that is firm and rigid. Conversely, synthetic tanning employs artificial chemicals such as glutaraldehyde and synthetic phenolic agents, offering a versatile range of leather characteristics based on the specific synthetic agents used (Nair & Rao, 2016).

The Emergence of Eco-Friendly Tanning Techniques

Recent trends in the leather industry have highlighted the need for sustainable tanning methods that reduce environmental impact without compromising leather quality (Thanikaivelan *et al.*, 2015). This shift has led to the development of bio-tanning and enzyme-assisted tanning processes, which utilize natural or biodegradable chemicals to achieve leather stabilization. Enzyme-assisted tanning, for instance, employs proteolytic enzymes to enhance the penetration of tannins or synthetic agents, thereby reducing the amount of chemicals required (Gassara *et al.,*2016). Similarly, the adoption of aldehyde-free synthetic tanning agents, which avoid the use of harmful substances like formaldehyde, represents a significant advancement in green leather processing. Additionally, the incorporation of plant-based and biodegradable tanning agents into existing processes is gaining popularity, as it aligns with global efforts to promote circular economy principles and reduce waste (Wu & Zhang, 2018; Patel & Sharma, 2018).

Environmental Implications of Tanning Processes

While the tanning industry has evolved considerably, it continues to face significant challenges related to environmental pollution and waste management. Effluents from traditional tanneries contain high levels of pollutants, including chromium, sulfides, and organic matter, which can have deleterious effects on aquatic life and human health if not adequately treated (Das *et al.,* 2015). In response to these concerns, regulatory frameworks have been established in many countries to enforce stricter waste management practices and encourage cleaner production technologies. Advances in wastewater treatment methods, such as membrane filtration, chemical precipitation, and biodegradation, have been integrated into tannery operations to mitigate the impact of leather processing on the environment (Cavani *et al.,* 2021). Besides, there is an ongoing effort to recycle and reuse tanning chemicals, mostly in chrome tanning, where spent chromium solutions can be recovered and restored into the tanning process (Taylor & Marmer, 2016).

Technological Innovations in Tanning

Technological innovations have played a crucial role in advancing tanning processes and improving leather quality (Thanikaivelan *et al.*, 2015). Modern tanning technologies, such as high-exhaustion tanning, which maximizes the uptake of tanning agents by the collagen matrix, and low-float tanning, which reduces water consumption, have been developed to enhance process efficiency and sustainability (Sundar *et al.*, 2016). Moreover, the integration of nanotechnology in leather processing has opened new avenues for the development of advanced leather materials with enhanced properties, such as improved water resistance, antimicrobial activity, and mechanical strength (Acar *et al.*, 2022). Nanomaterials, such as silver nanoparticles and carbon nanotubes, are being incorporated into leather finishes and coatings to impart novel functionalities and extend the leather's range of applications (Varghese & Nadarajan, 2016).

Economic and Industrial Relevance of the Leather Sector

The leather industry plays a significant role in the global economy, with applications extending across various sectors, including fashion, automotive, furniture, and sports. Leather goods are highly valued for their quality, durability, and aesthetic appeal, making them a preferred material in luxury items and high-performance products (Ferreira & Baptista, 2017). In addition to finished leather products, the industry generates valuable by-products, such as gelatin and collagen, which are used in the food, pharmaceutical, and cosmetic industries (Patel & Sharma, 2018). The valorization of leather waste through biotechnological processes has further enhanced the economic sustainability of the leather sector, aligning it with global trends toward resource efficiency and waste minimization (Zhou & Chen, 2021).

Raw Hides and Skins

Raw hides and skins refer to the untreated outer coverings of animals, predominantly from cattle, sheep, goats, and pigs (Sinha 2019). They form the primary raw material for the leather industry, which transforms them into durable and versatile products. The global leather industry relies heavily on hides and skins sourced from the meat and dairy industry, which ensures an abundant and sustainable supply (Hernández, 2022). Hides are typically sourced from larger animals like cows and buffaloes, while skins (Fig.3) are from smaller animals such as sheep and goats. The key difference lies in the thickness and structure; hides are generally thicker and coarser compared to skins (Covington, 2017; Patel & Sharma, 2018).

Fig. 3: Raw animal skin (Covington, 2017)

ChemicalComposition of Raw Hides and Skins

The primary component of hides and skins is collagen, a fibrous protein that provides the material's structural framework. Collagen fibers are interwoven into a network that gives the hide its strength and flexibility (Covington, 2017). In addition to collagen, raw hides contain other proteins, such as elastin and keratin, which contribute to elasticity and surface characteristics (Sinha, 2019). Water constitutes approximately 60-70% of raw hides, while fats and lipids make up around 2-5%, contributing to the flexibility and waterproof properties. Minerals like calcium, sodium, and phosphorus are also present, albeit in small quantities, and can influence the tanning process by affecting the pH and enzymatic reactions (Covington, 2017).

Properties of Raw Hides and Skins

The properties of raw hides and skins are crucial in determining their suitability for leather production. Key properties include tensile strength which is the ability to withstand stretching without tearing is vital for high-quality leather. The arrangement and density of collagen fibers largely influence this property.Also, raw hides possess some degree of elasticity, allowing them to stretch and recover. This property is enhanced or reduced during the tanning process. Lastly is the thermal stability. Collagen’s denaturation temperature is around 65°C for raw hides, and this stability increases significantly during tanning, which prevents leather from shrinking or hardening under heat (Patel & Sharma, 2018).

Classification of Tanning Agents

Tanning agents are substances used to convert raw hides and skins into leather by stabilizing the collagen fibers, making the material durable and resistant to decay. These agents can be classified based on their chemical structure, mechanism of action, and specific applications in leather processing (Hernández, 2022).

Classification Based on Chemical Structure

Mineral Tanning Agents

Mineral tanning uses metal salts, primarily chromium (III) sulfate, which is the most widely used tanning agent in the leather industry. The tanning process involves complexing chromium ions with the carboxyl groups on collagen. Basic chromium sulfate, represented as $[Cr(H_2O)_5(OH)]_2(SO_4)_3$ inFig.4 acts as the main source of chromium ions (Hernández, 2022). In this equation, R-COO^-(R-COO)-R-COO^-represents the carboxyl groups on collagen. The chromium ions bind with these groups, stabilizing the collagen structure and improving resistance to hydrolytic degradation. Other mineral tanning agents include aluminum salts (e.g., aluminum sulfate), zirconium salts, and iron salts. These agents are less commonly used compared to chromium but can be applied for specific leather properties (Thanikaivelan*et al.*, 2015).

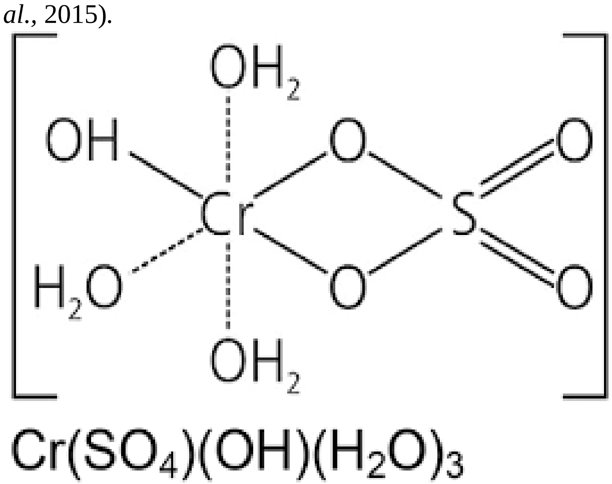


Fig. 4: Chemical structure of a mineral tanning agent

Vegetable Tanning Agents

Vegetable tanning employs natural tannins derived from plant sources such as oak, chestnut, and quebracho. These tannins consist of polyphenolic compounds, which are further classified as hydrolysable tannins andcondensed tannins.Composed of gallic acid or ellagic acid esterified with glucose, they can be hydrolyzed in water to release these acids. For example, tannic acid, a common hydrolysable tannin, can be hydrolyzed as follows:

Tannic Acid + H_2O → Gallic Acid + Glucose

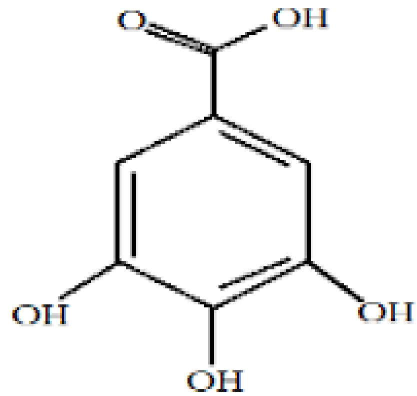


Fig. 5. Chemical structure of a hydrolysable tanning agent (Hernández, 2022)

Condensed Tannins is made up of flavonoid units such as catechin and epicatechin, these tannins do not hydrolyze easily in water and form stronger bonds with collagen. The cross-linking occurs through hydrogen bonding and hydrophobic interactions, providing the leather with a firm texture (Patel & Sharma, 2018).

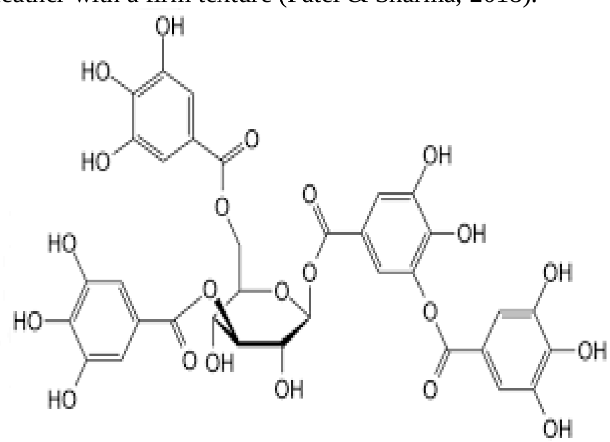


Fig. 6: Chemical structure of a condensed tannins as tanning agents

Synthetic Tanning Agents (Syntans)

Synthetic tanning agents are artificially produced chemicals designed to mimic the effects of traditional tannins. They are used either as primary tanning agents or for retanning purposes. Syntans include sulfonated aromatic compounds, formaldehyde-based agents, and acrylic or phenolic resins. Their mechanisms of action can involve ionic, covalent, or hydrogen bonding with the collagen structure.

Classification Based on Mechanism of Action

Cross-linking Tanning Agents

These agents chemically cross-link collagen fibers, making them more resistant to hydrothermal degradation. Mineral tanning (e.g., chromium salts) and aldehyde tanning (e.g., glutaraldehyde) fall into this category (Covington, 2017). Fig. 7 reveals the mechanism for cross-linking tanning agents.

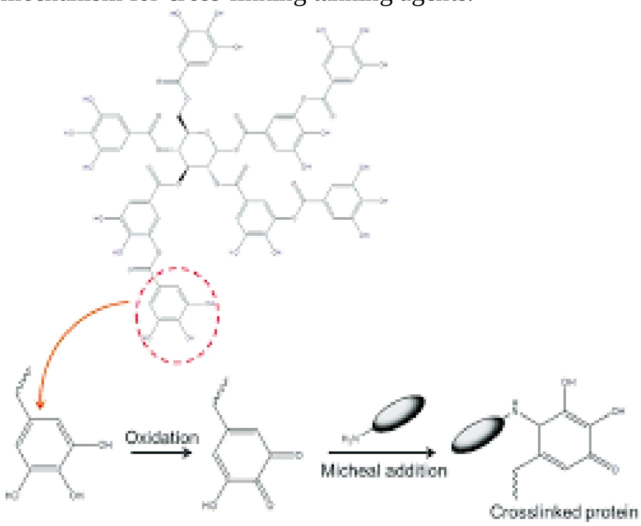


Fig. 7: Mechanism of cross-linking tanning agents

Non-Cross-linking Tanning Agents

Vegetable tannins and some syntans stabilize collagen without forming covalent cross-links (Fig. 8). Instead, they bind to collagen through hydrogen bonding and other physical interactions (Kumar & Sinha, 2019).

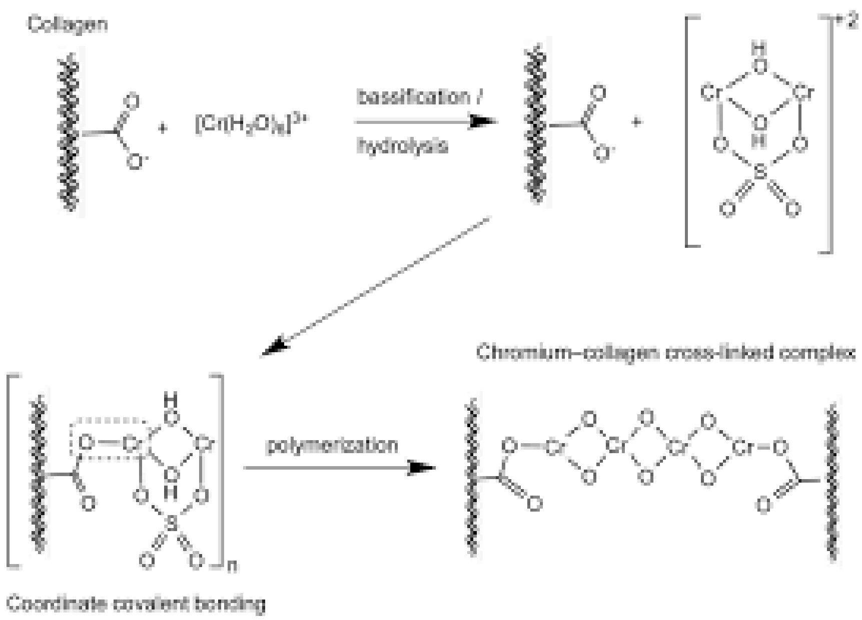


Fig. 8: Mechanism of non-cross-linking tanning agents **(**Kumar, 2019**)**

Combination Tanning Agents

These use a combination of different tanning mechanisms such as chrome-vegetable tanning, to impart multiple properties to the leather, enhances both strength and flexibility (Dixit *et al.*, 2015). This mechanism combination tanning agents is demonstrated in Fig. 9.

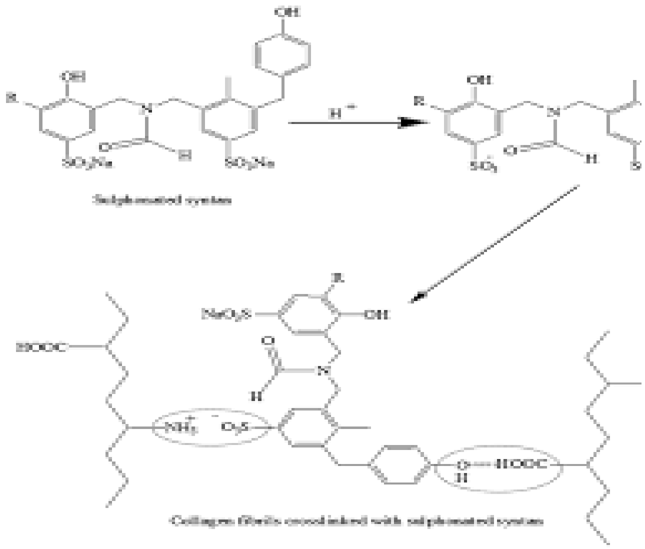


Fig. 9: Mechanism of combination tanning agents (Dixit *et al.*, 2015)

Classification Based on Applications
The choice of tanning agent is often guided by the desired properties and end-use of the leather. Thus, application-based classification includes are 1) Footwear and Saddlery for which vegetable tanning agents are preferred due to the resultant leather's firmness and durability, 2) Garment and upholstery leather in which chrome tanning is commonly used for producing soft, supple leather suitable for clothing and furniture, 3) Automotive leather which focuses on combination tanning, and often uses a blend of synthetic and chrome tanning agents, is employed to meet the high standards of resistance to heat and light, and Specialty leathers used for water-resistant or breathable leathers, aldehyde tanning (e.g., glutaraldehyde) or oil tanning may be applied to impart unique properties suitable for outdoor gear (Covington, 2017; Dixit *et al.*, 2015). Table 1 shows comparison of the various methods of tanning.

Table 1: Comparison of different tanning methods (Sinha, 2019)

Tanning Method	Main Chemical Agents	Leather Properties	Environmental Impact	Typical Applications
Chrome Tanning	Chromium(III) salts ($Cr_2(SO_4)_3$)	Soft, stretchable, high heat resistance	Toxic waste if not properly managed	Footwear, bags, automotive upholstery
Vegetable Tanning	Tannins from plant sources (e.g., oak, chestnut)	Firm, less stretchable, biodegradable	Low, eco-friendly, renewable sources	Belts, saddlery, traditional bookbinding
Synthetic Tanning	Phenol, formaldehyde, other synthetic resins	Moderate flexibility, good color fastness	Moderate; some synthetic agents are non-biodegradable	Upholstery, sports equipment
Aldehyde Tanning	Glutaraldehyde, oxazolidine	Soft, washable, white-colored leather	Minimal; safer than chrome but still involves chemicals	Medical leathers (e.g., gloves), baby shoes
Alum Tanning	Aluminum salts (e.g., aluminum sulfate)	White, pale, and non-durable	Low environmental impact	Traditional parchment, bookbinding

Tanning Chemistry
The chemistry of tanning encompasses the intricate interactions between tanning agents and collagen in raw hides, leading to the formation of stable leather. The tanning process relies heavily on cross-linking and stabilization mechanisms, both of which are pivotal in enhancing the durability and usability of leather (Dixit *et al.*, 2015).

Mechanisms of TanningCross-Linking
Cross-linking is essential for forming a stable network within the collagen fibers, significantly enhancing the properties of the resultant leather. This section discusses various tanning agents and their mechanisms, supported by relevant chemical equation (Yousup *et al.*, 2015).

Chromium Tanning
Chromium (III) ions play a critical role in cross-linking collagen fibers through the formation of stable coordinate bonds. The reaction can be represented as seen in the equation below. Here, chromium coordinates with two carboxylate groups from collagen, facilitating the formation of a robust cross-linked structure. This network enhances thermal stability, raising the collagen shrinkage temperature to above 100 °C, which is crucial for leather durability (Covington, 2017).

$$[Cr(H_2O)_6]^{3+} + 2R\text{-}COO^- \rightarrow [Cr(H_2O)_4(COO)_2]^+ + 2H_2O$$

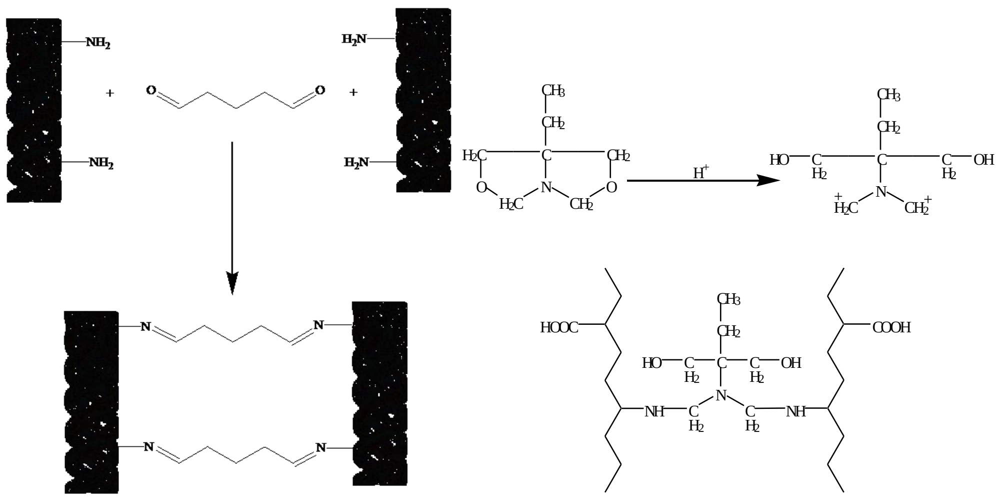
Vegetable Tanning
In vegetable tanning, polyphenolic compounds (tannins) from plants engage with collagen through hydrogen bonding and hydrophobic interactions. The process can be summarized by the following reaction below. This interaction forms a complex between tannins and collagen, stabilizing the fiber structure

without the extensive cross-linking seen in chromium tanning. The resulting leather is often firmer and is particularly suited for applications such as saddlery (Kumar & Sinha, 2019).

Tannin (OH)+Collagen ($-NH_2$)→ Tannin-O-H + N-H-Collagen

Aldehyde Tanning

Aldehyde tanning, such as using glutaraldehyde, involves the formation of imine bonds with collagen's amino groups as demonstrated in the equation below whereas Fig. 10 shows Mechanism of leather tanning with glutaraldehyde.This reaction leads to cross-linking through Schiff base formation, which not only enhances the water resistance of the leather but also provides hypoallergenic properties (Covington, 2017).



$$\text{R-CHO+NH}_2\text{-Collagen} \rightarrow \text{R-CH=N-Collagen+H}_2\text{O}$$

Fig. 10: Mechanism of leather tanning with glutaraldehyde (left) and oxazolidine (right) through cross-linking (Covington, 2017)

Synthetic Tanning (Syntans)

Synthetic tanning agents can interact with collagen through various mechanisms, including ionic and covalent bonding. An example of a sulfonated phenolic syntan reacting with collagen can be illustrated as: Sulfonated Phenol+Collagen → Syntan-Collagen Complex. This complex contributes to the specific properties desired in the final leather product, such as improved softness or color retention (Kumar & Sinha, 2019).

Mechanisms of Tanning Stabilization

Stabilization refers to the processes that enhance the resistance of collagen against hydrolytic, thermal, and microbial degradation. The following mechanisms detail how tanning contributes to stabilization, with corresponding chemical reactions (Dixit *et al*., 2015).

(i) Thermal Stabilization

The primary mechanism of thermal stabilization occurs through extensive cross-linking that raises the denaturation temperature of collagen. This transition illustrates that the collagen's thermal stability is markedly improved, allowing it to withstand temperatures exceeding 100°C without significant shrinkage (Covington, 2017). In chromium-tanned leather, the enhanced cross-linkingcan be expressed as shown in the equation below whereas the mechanism of leather tanning by enzymatic crosslinking with transglutaminase is demonstrated in Fig.11.

Collagen + Cr (III) → Cross-linked Collagen

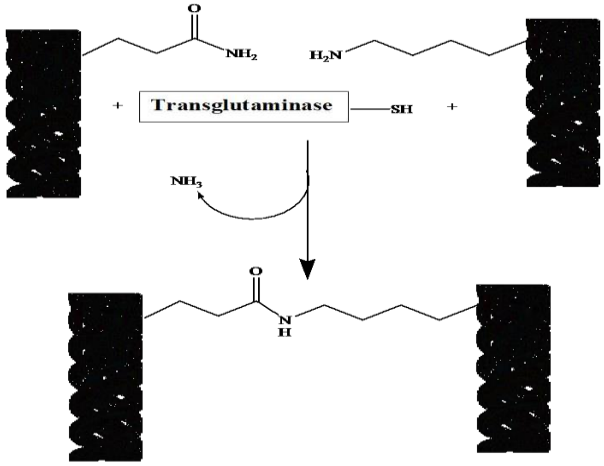


Fig. 11: Mechanism of leather tanning by enzymatic crosslinking with transglutaminase (Covington, 2017)

(ii) Hydrolytic and Enzymatic Stabilization

Tanning reduces the reactivity of collagen to hydrolysis and enzymatic degradation. The reaction showing the reduction of free amino groups during aldehyde tanning is as shown in the equation below. This reaction limits the number of available amino groups, thereby reducing hydrolytic attack and enhancing microbial resistance (Kumar & Sinha, 2019).

NH_2-Collagen + R-CHO → N=CH-R-Collagen + H_2O

Chemical Stabilization

Tanning modifies the chemical properties of collagen to further enhance stability. This modification alters the internal environment of the collagen, making it less susceptible to chemical degradation and enhancing overall leather quality (Dixit *et al.*, 2015). The process can be demonstrated through the reaction involving synthetic tanning agents as revealed in the following equation.

Synthetic tanning agent + Collagen →
Modified collagen structure

Leather Classification

Leather classification is crucial for understanding the characteristics and applications of various types of leather. This classification can be based on several criteria, including chemical composition, physical properties, and the intended use of the leather. This section will focus specifically on the chemical classification of leathers.

Chemical Classification of Leathers

Chemical classification of leathers involves categorizing them based on their structural and chemical properties, particularly concerning the tanning processes and the resulting quality of the leather. The main types include full-grain, top-grain, and split leathers.

(i) Full-Grain Leather: Full-grain leather is derived from the top layer of the hide and retains the natural grain pattern. This type is minimally processed and is tanned using various agents, such as chromium or vegetable tannins. The chemical composition of full-grain leather typically includes:

Collagen + Tanning agents →
Tanned collagen network

The preservation of the natural grain ensures that the leather retains its strength, breathability, and aesthetic appeal. Full-grain leather is highly durable and develops a patina over time, making it desirable for high-quality leather goods (Covington, 2017).

(ii)Top-Grain Leather: Top-grain leather is also sourced from the top layer of the hide but is sanded or buffed to remove imperfections. This process results in a smoother surface but reduces some of the leather's natural characteristics. The tanning process can be represented as seen below.

Collagen + Tanning agents + Finishing agents→
Refined tanned collagen

The addition of finishing agents (such as dyes and coatings) alters the surface chemistry, providing a more uniform appearance. While top-grain leather is slightly less durable than full-grain, it is more resistant to stains and easier to maintain (Kumar & Sinha, 2019).

(iii)Split Leather: Split leather is produced from the lower layers of the hide, which are separated from the top layer during the tanning process. The split can be further processed into suede or other finishes. The chemical structure of split leather can be expressed as represented below (Zhang et al., 2019).

Lower layer collagen + Tanning agents →
Tanned split leather

This type of leather is generally less durable than full-grain or top-grain leather but can be treated and finished to enhance its appearance and usability. Suede, derived from split leather, is known for its soft texture but is less resistant to moisture and staining compared to full-grain and top-grain leather (Dixit et al., 2015).

Chemical Properties and Considerations

The chemical properties of these leather types are primarily influenced by the choice of tanning agents used. The primary protein in leather, collagen, maintains its structural integrity through cross-linking with tanning agents. The type of tanning (chrome, vegetable, or synthetic) affects the density and stability of the collagen network. Various chemical treatments post-tanning, including dyeing and finishing, can further modify the properties of the leather. For example, the use of aniline dyes in top-grain leather enhances its color without masking the natural grain (Faisal *et al.*, 2018).Full-grain leather's natural oils and fibers contribute to its durability and the development of a unique patina with age. In contrast, top-grain leather's treated surface may wear differently due to its altered chemical structure (Hernández 2022).

Leather Composition

The composition of leather is a crucial aspect that influences its physical properties, durability, and suitability for various applications. Understanding the chemical constituents of leather-primarily proteins, lipids, and tanning agents-provides insights into its quality and performance. (Zhang et al., 2019).Chemically, leather is primarily composed of organic materials, with collagen being the main structural protein. Other components, such as lipids and tanning agents, play significant roles in determining the properties of the leather. This section discusses these components in detail (Hernández, 2022). Fig. 12 shows the chemical composition of leather.

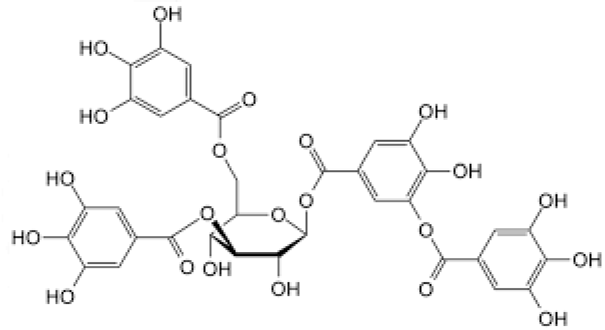


Fig. 12. Chemical composition of leather

Proteins

Collagen is the predominant protein in leather, constituting approximately 80-90% of its dry weight. It provides strength and flexibility. The structure of collagen can be represented by the triple helix formation of its polypeptide chains (Gly-Pro-X)n (Hernández, 2022), as shown in the Fig. 13.

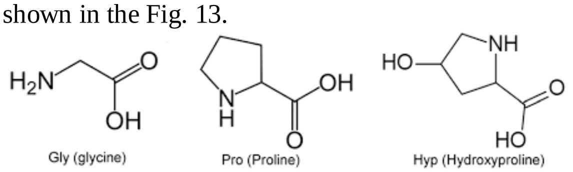


Fig. 13: Chemical structure of collagen with triple helix formation of its polypeptide chain

Where Gly is glycine, Pro is proline, and X can be any amino acid. The cross-linking of collagen molecules during tanning enhances the strength and thermal stability of leather. The reaction during chromium tanning can be expressed in the chemical expression below. This reaction illustrates the bonding between collagen and chromium ions, forming a cross-linked network (Covington, 2017).

Collagen-NH_2+Cr(III)→Collagen-Cr(III)+H_2O

Aside from collagen, leather may contain other proteins such as elastin and keratin, which contribute to specific properties like elasticity and surface texture. The presence of these proteins can vary depending on the type of hide used.

Lipids

Lipids in leather, though constituting a smaller fraction (approximately 3-10%), are essential for providing moisture resistance and flexibility. The main types of lipids present include: Fatty acids such as stearic acid and oleic acid contribute to the hydrophobic properties of leather. The interaction of fatty acids with collagen can be simplified in the equation below. This esterification reaction enhances water repellency and softness (Dixit *et al*., 2015).

Collagen-OH + Fatty acid → Collagen-ester + H_2O

In addition,natural oils and waxes are often used in leather finishing to improve the surface finish and water resistance. They form a protective layer on the leather's surface, contributing to its aesthetic appeal and durability (Hernández 2022).

Tanning Agents

Tanning agents are crucial for converting raw hides into durable leather. The choice of tanning agent affects the chemical composition and properties of the final product. Common tanning agents include chromium salts, vegetable tannins and synthetic tanning agents.

(i) Chromium Salts: Chromium salts are widely used due to their efficiency in cross-linking collagen. The chemical interaction during tanning can be represented as seen in the equation shown below. The presence of Cr (III) ions facilitate the formation of strong coordinate bonds, enhancing the mechanical strength and durability of leather (Kumar & Sinha, 2019). Fig. 14 show a schematic illustration of leather tanning process with Cr-nanoparticles.

Collagen-NH_2+Cr (III) → Collagen-Cr (III) + H_2O

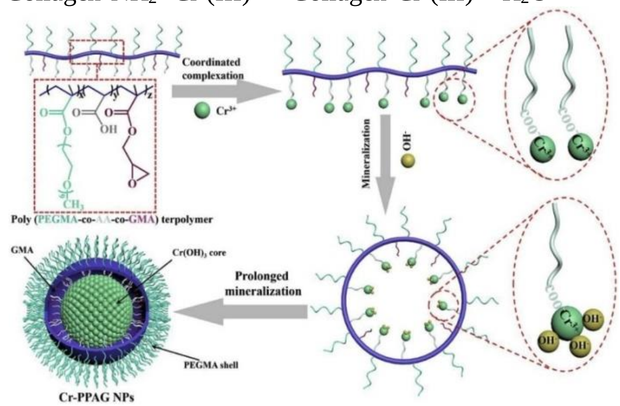


Fig. 14: Schematic illustration of leather tanning process with Cr-nanoparticles (Kumar, 2019)

(ii)Vegetable Tannins: Vegetable tannins are natural polyphenol compounds that react with collagen through hydrogen bonding. The process can be summarized in the expression below.This interaction results in a more rigid structure, improving the leather's resistance to environmental factors (Dixit *et al*., 2015).According to Hassan *et al.* (2023), the mechanisms of tanning of leather with vegetable tannins is demonstrated in Fig. 15.

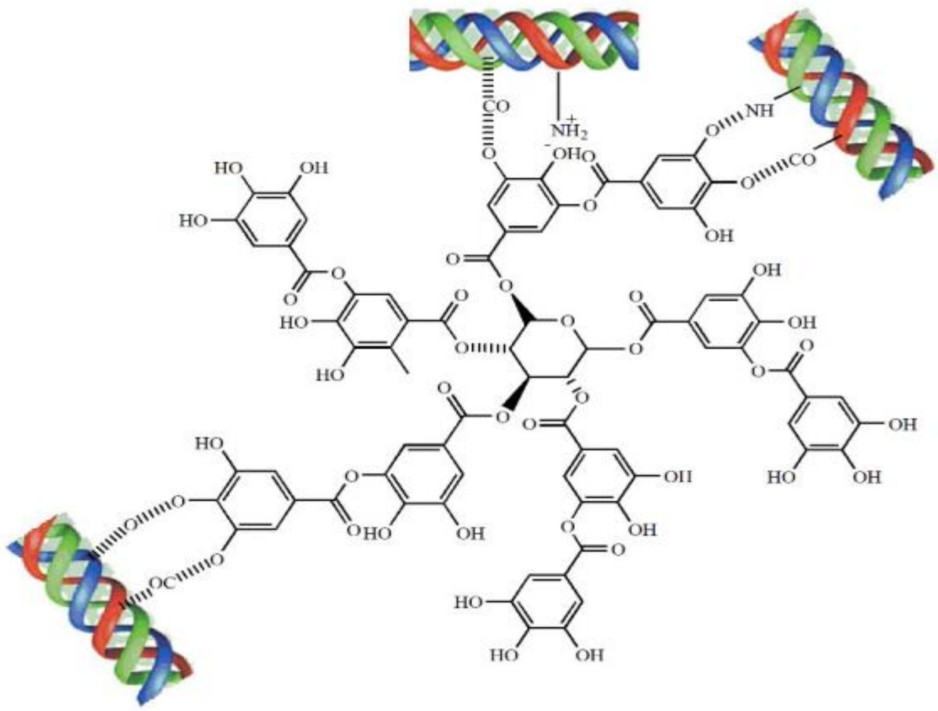


Fig15. Mechanisms of tanning of leather with vegetable tannins (Hassan *et al.*, 2023)

Tannin (OH) + Collagen ($-NH_2$)→ Tannin-Collagen Complex

(iii) Synthetic Tanning Agents: Synthetic tanning agents, such as aldehydes, provide alternatives to traditional tanning methods. For instance, glutaraldehyde reacts with amino groups in collagen as follows:

$R\text{-}CHO + NH_2\text{-}Collagen \rightarrow R\text{-}CH{=}N\text{-}Collagen + H_2O$

The formation of imine linkages enhances the stability and durability of leather. The chemical composition of leather is predominantly characterized by collagen, along with lipids and tanning agents that significantly influence its properties. Understanding these components is vital for producing high-quality leather suitable for various applications, from fashion to upholstery (Covington, 2017).

Table 2: Common chemicals used in leather processing and their functions (Covington, 2017)

Chemical	Stage of Processing	Function	Effect on Leather Properties
Sodium Sulfide (Na_2S)	Unhairing (liming)	Helps remove hair from the hide by breaking down keratin	Can make the leather weaker if overused
Calcium Hydroxide ($Ca(OH)_2$)	Liming	Swells the hide, facilitating the removal of flesh and hair	Affects the final softness and pliability
Chromium(III) Sulfate ($Cr_2(SO_4)_3$)	Tanning (chrome tanning)	Cross-links collagen fibers, stabilizing the hide	Increases heat and water resistance
Tannic Acid ($C_{76}H_{52}O_{46}$)	Tanning (vegetable tanning)	Forms a leather with firmer structure	Improves biodegradability, retains natural color.
Glutaraldehyde ($OHC(CH_2)_3CHO$)	Tanning (aldehyde tanning)	Used as an alternative to chrome; non-toxic	Produces a softer, white leather
Fat Liquors (e.g., Sulfated Oils, $R\text{-}O\text{-}SO_3^-\ Na^+$)	Fatliquoring (post-tanning treatment)	Adds softness and water-repellency	Enhances leather's flexibility and smoothness
Dyes and Pigments (Variable)	Dyeing and Finishing	Provides color to the finished leather	Contributes to aesthetics and color fastness

Formaldehyde (CH_2O)	Retanning and Finishing	Improves the grain tightness and reduces stretch	Can affect breathability if used excessively

Leather Properties

The properties of leather are largely determined by the underlying chemical structure and interactions among collagen, tanning agents, and other components. Understanding these chemical bases provides insight into why leather possesses specific qualities such as strength, flexibility, and water resistance.

Chemical Basis for Leather Properties

Strength: The strength of leather is mainly attributed to the cross-linking of collagen fibers during tanning. For instance, chromium tanning involves the formation of coordinate bonds between chromium ions and carboxyl groups in collagen, creating a stable cross-linked network as revealed below. This cross-linking not only reinforces the structural integrity but also increases tensile strength (Heidemann, 2016; Thanikaivelan *et al.*, 2015).

$[Cr(H_2O)_6]^{3+} + 2R\text{-}COO^- \rightarrow [Cr(H_2O)_4(COO)_2]^+ + 2H_2O$

Flexibility: Flexibility is achieved through the preservation of collagen's triple-helix structure, which allows for a degree of movement within the leather matrix. Vegetable tanning, for example, uses tannins to form hydrogen bonds with collagen, which allows for some elasticity while maintaining the leather's structure as shown below. The hydrogen bonds are relatively weaker compared to covalent bonds, allowing for more flexibility (Liu *et al.*, 2017).

Tannin-OH+Collagen-NH_2 $\rightarrow$Hydrogen bonded complex

Water Resistance: Water resistance in leather arises from the hydrophobic properties imparted by certain tanning agents and the treatment with oils or waxes. For example, aldehyde tanning creates hydrophobic imine linkages, which reduce the water affinity of the collagen matrix as seen below. The addition of oils, such as lanolin, further enhances water resistance by forming a hydrophobic coating on the leather's surface (Chen *et al.*, 2018).

$R\text{-}CHO + NH_2\text{-}collagen \rightarrow R\text{-}CH{=}N\text{-}collagen + H_2O$

Table 3: Chemical composition of different types of leather (Chen *et al.*, 2018)

Leather Type	Moisture content (%)	Fat content (% dry weight)	Chromium content (mg/kg)	Shrinkage temperature (°C)
Chrome-Tanned Leather	12-18	4-8	2000-3500	100-110
Vegetable-Tanned Leather	14-20	3-6	<10 (trace)	75-85
Aldehyde-Tanned Leather	16-22	2-5	<5 (trace)	70-80
Synthetic-Tanned Leather	10-15	5-10	<5 (trace)	85-95
Alum-Tanned Leather	18-24	2-4	<10 (trace)	65-75

Leather Tanning Processes

Tanning processes convert raw hides into leather by chemically stabilizing collagen fibers, which makes them resistant to decomposition. Different tanning methods result in varying leather properties.

Vegetable Tanning

Vegetable tanning uses tannins derived from plant sources (e.g., oak bark, chestnut). The process involves polyphenolic compounds forming hydrogen bonds with collagen as demonstraction by the reaction below. This results in a firmer leather with a natural appearance, often used in traditional crafts like saddlery. The tannin-collagen interactions provide stability against bacterial degradation but may result in less flexibility compared to chrome-tanned leather (Thanikaivelan *et al.*, 2015).

Tannin (OH)+Collagen (-NH_2)$\rightarrow$Tannin-Collagen Complex

Chrome Tanning

Chrome tanning involves using chromium(III) salts, which react with carboxyl groups in collagen to form strong covalent and coordinate bonds which is highlighted in the reaction below. This method provides superior flexibility, water resistance, and heat stability. Chrome tanning is faster than vegetable tanning and results in a leather with a blue-grey color, known as wetblue leather, which is then further processed and dyed (Kanagaraj *et al.*, 2015).

$[Cr(H_2O)_6]^{3+} + 2R\text{-}COO^- \rightarrow [Cr(H_2O)_4(COO)_2]^+ + 2H_2O$

Synthetic Tanning

Synthetic tanning, or syn-tanning, involves the use of synthetic tanning agents, such as aldehydes and phenol-based syntans. These agents react with collagen's amine groups to form chemical linkages as shown below. Synthetic tanning can be used to customize the leather properties by controlling the degree of cross-linking and adding specific functionalities, such as antimicrobial properties or color retention (Chen *et al.*, 2018).

$R\text{-}CHO + NH_2\text{-}Collagen \rightarrow R\text{-}CH{=}N\text{-}Collagen + H_2O$

Collagen Chemistry

Collagen, the primary protein in leather, plays a vital role in determining the material's properties. Its chemical characteristics and reactions during the tanning process directly impact the final quality of leather.

Chemical Properties and Reactions of Collagen

Triple-Helix Structure: Collagen's unique triple-helix structure comprises three polypeptide chains coiled around each other, providing strength and stability. The amino acid sequence typically follows a repeating pattern of glycine-proline-X, where X can be any amino acid:$(Gly\text{-}X\text{-}Y)_n$.This structure is crucial for the collagen's ability to form stable cross-links during tanning (Heidemann, 2016).

Reactivity with Tanning Agents The amino groups ($-NH_2$) and carboxyl groups (-COOH) in collagen are reactive sites that interact with tanning agents. For instance, during chrome tanning, chromium ions bind with the carboxyl groups to form a stable cross-linked network:

$[Cr(H_2O)_6]^{3+} + 2R\text{-}COO^- \rightarrow [Cr(H_2O)_4(COO)_2]^+$

Similarly, aldehyde tanning results in Schiff base formation through reactions between aldehydes and the amino groups in collagen as seen below. These reactions stabilize the collagen, preventing degradation and increasing durability (Thanikaivelan*et al.*, 2015).

$R\text{-}CHO + NH_2\text{-}Collagen \rightarrow R\text{-}CH{=}N\text{-}Collagen$

Retanning and Finishing

Retanning and finishing are essential steps in leather processing that aim to enhance the leather's properties, such as color, feel, and durability. Retanning involves additional treatment with tanning agents after the primary tanning process, while finishing includes surface treatments to achieve the desired appearance and functional characteristics. Fig.16 shows a pictorial demonstration of a finished leather (Faisal *et al.*, 2018)

Figure 16: Pictorial illustration of a finished leather (Faisal *et al.*, 2018)

Chemical Processes and Agents used in Retanning and Finishing

(i)Retanning: Retanning helps to adjust the fullness, softness, and dye uptake of the leather. This process often utilizes synthetic tanning agents (syntans), vegetable tannins, and resins. For example, acrylic syntans and phenolic resins are commonly used for retanning: Acrylic Acid + Ammonia → Acrylic Resin.Acrylic syntans help fill the leather structure, providing a smooth, uniform texture and increasing dye affinity (Thanikaivelan *et al.*, 2015).

(ii)Finishing: The finishing process involves coating the leather surface with various substances such as pigments, dyes, and protective agents. Typical finishing agents include casein, polyurethane, and acrylic emulsions, which form a protective layer on the surface to enhance water resistance and durability: Polyurethane (PU) Prepolymer+ Crosslinker→ PU Coating. The application of polyurethanes provides a glossy finish and improves abrasion resistance (Covington, 2017).

Leather Dyeing and Pigmentation

Dyeing and pigmentation processes impart color to the leather. These processes involve chemical interactions between dyes, pigments, and the leather's fibrous structure.

Chemical Principles of Leather Dyeing and Pigmentation

(i) Dyeing Principles: Leather dyeing relies on the affinity of the dye molecules for the collagen fibers. This can involve ionic, hydrogen, or covalent bonding, depending on the type of dye used. For example, acid dyes form ionic bonds with the basic sites on collagen revealed in the expression below.The $-NH_2$ groups on collagen interact with the anionic sites of the dye, leading to a strong color fixation (Sundararajan *et al.*, 2016).

$Dye\text{-}SO_3H + NH_2\text{-}Collagen \rightarrow Dye\text{-}SO_3\text{-}Collagen + H_2O$

(ii)Pigmentation Principles: Pigments are insoluble particles that coat the leather surface rather than penetrating the fiber. Pigments are fixed to the leather using binders, such as polyurethane or acrylic resins, which hold the pigment particles in place (Sundararajan*et al.*, 2016).

Chemical Agents Used in Leather Dyeing and Pigmentation

(i)Acid Dyes: Acid dyes are commonly used for their ability to bind to the amino groups in collagen, providing vibrant and durable colors. **(ii) Pigments:** Pigments used in leather finishing include inorganic pigments (e.g., titanium dioxide for white) and organic pigments (e.g., azo dyes for vibrant colors). The pigments are dispersed in a binder matrix to achieve an even application on the leather surface.

Chemical Processes and Agents Used in

Fatliquoring and Softening

Fatliquoring is the process of adding oils and lubricants to the leather to impart softness, flexibility, and waterproofing properties.

(ii) Fatliquoring Process: Fatliquoring involves the penetration of oil or fat emulsions into the leather fibers. These substances react with the collagen to form a lubricating layer that prevents the fibers from sticking together. This reaction enhances the softness and flexibility of the leather (Covington, 2017):

Oil (R-COOH) + Collagen-NH_2→Collagen-Oil Ester + H_2O

(ii) Common Fatliquoring Agents: Emulsified oils (e.g., sulfated fish oil), synthetic lubricants, and natural fats (e.g., lanolin) are commonly used in fatliquoring. These agents provide a balance between softness and water resistance.

Leather Defects and Faults

Leather defects can arise from a variety of chemical, mechanical, or biological factors. Understanding the chemical causes of these defects helps in implementing effective remedies (Sundararajan *et al.,* 2016).

Special Leathers

Special leathers refer to types of leather that undergo specific treatments to achieve distinctive textures, finishes, or properties. Suede, nubuck, and patent leather are prominent examples, each featuring unique processing methods and chemical treatments.

Chemical Properties of Special Leathers

Suede: Suede is made from the inner layer of the hide, giving it a soft and fuzzy texture. It is achieved by sanding or buffing the flesh side of the leather. Chemically, suede has more exposed collagen fibers due to the removal of the grain layer, making it more absorbent and less resistant to water and staining (Sundararajan *et al.,* 2016). To enhance water resistance and durability, protective finishes such as silicone or fluoropolymer treatments are applied: Silicone Resin + Collagen → Water-resistant Suede. The application of silicones creates a hydrophobic layer on the leather fibers, reducing water absorption (Liu *et al.*, 2017).

Nubuck: Nubuck is similar to suede but is made by sanding the grain side of the leather. It has a finer texture and more uniform appearance compared to suede. The chemical properties of nubuck involve the modification of the grain layer, making it more sensitive to oils and stains. Treatments with Fluorochemical finishes can impart stain resistance:Fluoropolymer Treatment + Leather Surface → Stain-resistant Nubuck.Fluorochemical coatings reduce the surface energy of the leather, preventing the penetration of liquids and dirt (Chen *et al.,* 2018).

Patent Leather: Patent leather features a glossy, high-shine finish achieved by coating the surface with a lacquer or plastic-based material, such as polyurethane. The coating provides a sealed surface, making patent leather more water-resistant than other types of leather. Chemically, the polyurethane or acrylic coatings act as a protective barrier:Polyurethane Prepolymer+ Crosslinking Agent → PU-coated Patent Leather. The high-gloss finish results from the smooth, continuous polymer film that forms on the leather surface (Covington, 2017).

Chemical Applications of Special Leathers

(i) Suede Applications: Suede is valued for its softness and texture, making it suitable for fashion items such as shoes, jackets, and bags. However, due to its porous nature, suede is often treated with water-repellent agents like silicones or wax emulsions to enhance its suitability for outdoor applications (Sundararajan *et al.,* 2016). **(ii) Nubuck Applications:** Nubuck's velvety texture and elegant appearance make it popular in high-end footwear and furniture. To improve its usability, nubuck is treated with stain-resistant chemicals and protective coatings that increase its durability against spills and oils (Thanikaivelan *et al.,* 2015). **(iii) Patent Leather Applications:** The distinctive shine of patent leather makes it suitable for formal footwear, handbags, and accessories. The chemical coatings used in patent leather not only provide an aesthetic appeal but also protect the leather from environmental factors, extending its lifespan. Additionally, patent leather is used in automotive interiors and decorative applications where a sleek, polished look is desired (Thanikaivelan *et al.*, 2015).

Chemical Causes and Remedies for Leather Defects and Faults

Chromium Staining: Chromium stains can occur if the chrome tanning process is not properly controlled, leading to residual chromium salts on the leather surface. The remedy involves thorough washing and neutralization to remove excess chromium.

Acid Rot: Acid rot results from residual acids in the leather, leading to hydrolytic degradation of collagen (Thanikaivelan *et al.,* 2015). This can be remedied by careful pH control during processing and the use of neutralizing agents such as sodium bicarbonate:

$H_2SO_4+2NaHCO_3 \rightarrow Na_2SO_4+2CO_2+2H_2O$

Fatty Spew: Fatty spew refers to the migration of fats to the surface of the leather, forming a whitish deposit. It can be prevented by using fatliquoring agents that are more chemically stable or applying additional surface treatments to lock the fats in place (Heidemann, 2015).

Applications of leather

Leather is a versatile material with a wide range of applications across various industries due to its durability, aesthetic appeal, and comfort. Here are some key applications of leather include:

Fashion and Apparel

(i) Clothing: Leather is commonly used in the production of jackets, trousers, skirts, and dresses. Its natural properties provide warmth and protection. **(ii) Footwear**: Leather is a popular choice for shoes, boots, and sandals because of its durability and ability to mold to the shape of the foot **(iii) Accessories**: Items such as belts, bags, wallets, and gloves are often made from leather, offering both style and longevity (Thanikaivelan *et al.*, 2015).

Automotive Industry

Upholstery: Leather is widely used for car interiors, including seats, dashboards, and steering wheels, due to its luxurious feel and easy maintenance.**Trim and Detailing**: Leather enhances the aesthetic appeal of vehicles, providing a premium look and feel (Thanikaivelan *et al.*, 2015).

Furniture

Upholstered Furniture: Leather is commonly used in sofas, chairs, and recliners, offering durability and ease of cleaning.**Decorative Items**: Leather is also used for cushions, ottomans, and other decorative pieces that enhance interior design (Thanikaivelan *et al.,* 2015).

Sporting Goods

Equipment: Leather is used in various sports equipment, such as footballs, basketballs, and gloves, because of its resilience and grip.**Protective Gear**: Items like leather pads, helmets, and other protective gear are made to provide safety and comfort during sports activities (Faisal et al., 2018).

Industrial Applications

Protective Clothing: Leather is used to make protective gear for workers in various industries, including welding, firefighting, and construction, due to its resistance to abrasions and cuts.**Belting and Lining**: Leather is used in manufacturing conveyor belts and linings for machinery due to its strength and durability.

Art and Craft

Leather Goods: Craftspeople create various leather items, including handmade bags, wallets, and accessories, often employing traditional techniques. **Bookbinding**: Leather is used for high-quality book covers and bindings, offering both durability and a classic aesthetic.

Medical Applications

Surgical Instruments: Leather is sometimes used in the manufacturing of handles for surgical instruments and other medical tools, providing a comfortable grip.**Orthopedic Supports**: Leather is used in the production of orthopedic supports and braces, providing both support and durability.

Aerospace Industry

Interior Finishes: Leather is used in aircraft interiors for seating and trim, enhancing comfort and aesthetics while being lightweight.

Home Decor

Wall Treatments: Leather is used in wall panels and coverings, providing a luxurious finish to interiors.

Bedding: Leather is sometimes used in bedding products such as headboards and decorative pillows.

Ongoing Challenges and Future Directions in Tanning Chemistry

Despite significant advancements, the leather industry continues to face challenges related to sustainability, resource management, and the development of safe and efficient tanning agents (Thanikaivelan *et al.,* 2015). Addressing these challenges requires a multidisciplinary approach that combines advances in chemistry, materials science, and environmental engineering (Hernández, 2022). The pursuit of chrome-free tanning solutions, the development of biodegradable synthetic agents, and the use of renewable resources for tanning chemicals are key areas of ongoing research. The leather industry's future lies in balancing technological innovations with environmental stewardship, ensuring that leather remains a versatile and sustainable material for generations to come (Yang & He, 2023).

CONCLUSION

Leather tanning is a complex chemical process that converts raw animal hides into a durable, versatile material by stabilizing the protein structure, mainly collagen, to prevent decomposition and enhance physical properties. This transformation is achieved using various tanning agents, which are broadly classified into mineral, vegetable, and synthetic categories. Each type has unique chemical properties that interact differently with the collagen matrix to impart specific characteristics to the leather. Mineral tanning, particularly chrome tanning, is the most prevalent method due to its ability to produce leather with superior flexibility and heat resistance. This process involves the formation of stable cross-links between chromium ions and the carboxyl groups in collagen, providing a robust and durable final product. In contrast, vegetable tanning uses polyphenolic compounds from plant sources, forming hydrogen bonds and hydrophobic interactions with the collagen, resulting in a firmer, more natural-looking leather. Synthetic tanning agents, such as sulfonated phenols and acrylic resins, allow for greater customization of leather properties, making them suitable for specialized applications.

The chemical composition of leather is not limited to collagen but also includes residual tanning agents, fats, dyes, and pigments introduced during processing. These components contribute to the leather's final characteristics, including strength, softness, and appearance. Retanning and finishing processes further modify the leather, providing enhanced fullness, color, and surface texture. Techniques such as fatliquoring are crucial in maintaining leather's softness by introducing oils that lubricate the fibers. Additionally, dyeing and pigmentation processes rely on the chemical interaction between dyes, pigments, and the

leather matrix to achieve desired colors and visual effects.
Collagen's unique structure, comprising a triple-helix arrangement of amino acids, is central to the tanning process. Its reactivity to various chemical agents allows for diverse tanning methods that stabilize and modify its properties, making it resistant to hydrolysis, heat, and microbial degradation. Understanding collagen's chemistry enables the optimization of tanning processes to achieve desired outcomes, such as increased tensile strength, improved thermal stability, and specific aesthetic qualities. The seminar has also highlighted the classification of leathers based on their finishing processes, including full-grain, top-grain, and split leathers, each having distinct chemical properties resulting from different processing techniques.
Despite its advancements, the leather industry faces significant environmental and health challenges, particularly from the widespread use of chromium salts in tanning, which can lead to hazardous waste. Consequently, there is a growing need for sustainable practices, such as replacing toxic tanning agents with bio-based alternatives, implementing waste recycling, and adopting cleaner technologies. The development of eco-friendly tanning methods, such as enzyme-assisted processes and the use of biodegradable tanning agents, presents opportunities for reducing the ecological footprint while maintaining leather quality. Advances in synthetic tanning and nanomaterial applications also hold promise for more efficient leather production with minimal environmental impact.
Generally, the chemistry of leather tanning is integral to the production of a wide range of leather products, from footwear and clothing to automotive and furniture upholstery. The field continues to evolve as the industry seeks to improve leather quality, meet consumer demands, and address environmental concerns. By embracing sustainable innovations and enhancing the understanding of tanning chemistry, the leather industry can continue to thrive, balancing the traditional craftsmanship with modern environmental and technological standards. The seminar concludes that the future of leather tanning lies in integrating scientific advancements with sustainable practices, ensuring that leather remains a valuable and eco-conscious material in the years to come.

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