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EVALUASI PENGOLAHAN KULIT DALAM KERANGKA INDUSTRI RAMAH LINGKUNGAN: IMPLIKASI TERHADAP PEMANFAATAN BERKELANJUTAN PRODUK SAMPING PETERNAKAN

EVALUATING THE PROCESSING OF HIDES WITHIN A GREEN INDUSTRY FRAMEWORK: IMPLICATIONS FOR SUSTAINABLE LIVESTOCK BY-PRODUCT UTILIZATION

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Abstract. *The processing of animal hides into leather represents a critical interface between livestock systems and green industrial development, yet it remains environmentally intensive due to conventional chrome-based tanning practices. While cleaner tanning technologies have been widely studied, existing reviews often examine individual methods without sufficiently linking hide processing, livestock by-product utilization, and technological readiness within a green industry framework. This review critically evaluates recent developments in hide processing technologies (including enzymatic treatments, vegetable tanning, and emerging bio-based and polysaccharide tanning agents) through the lens of a circular livestock-based bioeconomy. A systematic literature review was conducted using major scientific databases to assess these approaches in terms of processing efficiency, environmental performance, leather quality, and implementation feasibility. The analysis indicates that enzymatic processes function primarily as process enablers, with reported reductions in sulfide consumption of approximately 30–70%, alongside 20–50% decreases in BOD and COD loads and shorter processing times compared with conventional lime–sulfide systems. In contrast, vegetable tanning effectively eliminates chromium-based pollutants but remains associated with elevated organic effluent loads due to residual polyphenolic compounds. Emerging bio-based and polysaccharide tanning systems demonstrate promising leather performance and hydrothermal stability; however, their broader application is constrained by scalability, raw material availability, and limited industrial validation. The novelty of this review lies in its system-oriented synthesis that positions hide processing as an integrative pathway connecting sustainable livestock by-product utilization, cleaner tanning technologies, and green industrial development. By highlighting quantitative environmental benefits alongside technological trade-offs and adoption challenges, this review provides a realistic framework for advancing sustainable leather production within a circular bioeconomy.*

Keywords : *Circular leather industry, Enzymatic tanning, Hide Processing, Livestock by-product utilization*

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INTRODUCTION

The leather industry plays a significant role in the global economy, particularly through the export of footwear, garments, and automotive leather products (Zhang & Chen, 2020). However, this economic contribution is accompanied by substantial environmental challenges, primarily associated with conventional tanning processes that rely heavily on chromium salts and intensive chemical inputs. These practices generate hazardous effluents, heavy metal contamination, and high organic loads, placing increasing pressure on environmental sustainability and regulatory compliance.

In response, a growing body of research has explored green, enzymatic, vegetable, and chrome-free tanning technologies aimed at reducing the environmental footprint of leather processing. Nevertheless, most existing studies and reviews remain focused on individual process improvements or specific alternative tanning agents. Comparatively limited attention has been given to the systemic integration between livestock derived raw materials, waste valorization pathways, and cleaner tanning technologies within a unified circular bioeconomy framework. Moreover, comparative evaluations that critically assess enzymatic, vegetable, and emerging bio-based tanning methods in terms of processing efficiency, environmental performance, leather quality, and technological readiness remain fragmented.

Beyond tanning agents themselves, biomass-based solutions for pollution mitigation further highlight the untapped potential of circular approaches. Certain biological materials, including fungi growing in tannery sludge, have demonstrated the ability to absorb or transform heavy metals such as chromium. For example, *Fusarium* sp. can reduce toxic Cr(VI) to the less harmful Cr(III), while *Mucor* sp. exhibits chromium adsorption capacity, as evidenced by observable color changes in treated solutions (Triatmojo & Wibowo, 2012). These findings reinforce the potential role of biomass waste not only as a remediation tool but also as an integral component of circular resource utilization in the leather industry.

Within the Indonesian context, the relevance of such approaches is particularly pronounced. Indonesia possesses abundant local biomass resources including rice husks, coconut shells, and fishery by-products that could be utilized for tanning processes or wastewater treatment. However, research on these materials remains scattered and underexplored, and their integration into existing tanning systems has not been systematically analyzed. As a result, opportunities to reduce dependence on imported chemicals, lower production costs, and mitigate environmental impacts are yet to be fully realized, especially for small and medium-sized enterprises (SMEs).

This review addresses these gaps by positioning cleaner tanning technologies within the broader context of circular livestock systems, emphasizing the functional role of enzymatic processes and biomass-derived tanning agents as enablers of closed-loop resource flows. Rather than viewing enzymatic and bio-based tanning as standalone alternatives, this study synthesizes recent advances to evaluate their techno-environmental performance, adoption barriers, and practical trade-offs, with particular attention to developing country contexts.

Accordingly, the objectives of this review are to:

1. Critically evaluate conventional and emerging tanning technologies from environmental, technical, and economic perspectives;
2. Identify key research gaps and barriers affecting the scalability and industrial adoption of cleaner tanning methods; and
3. Propose a circular techno-economic framework that integrates enzymatic tanning with the valorization of local biomass waste to enhance sustainability and competitiveness in the leather industry.

Although enzymatic tanning exhibits substantial ecological advantages such as reduced chemical consumption, lower wastewater loads, and improved process efficiency its broader implementation remains constrained by cost, scalability, and limited compatibility with existing SME-based infrastructure. Therefore, this review argues that future progress depends not only on the development of new tanning agents, but also on the establishment of a circular techno-economic model capable of achieving commercial viability. The proposed conceptual framework of this circular bioeconomy approach is presented in Figure 1, illustrating an integrated pathway toward a sustainable leather industry in developing countries.

Figure 1. Conceptual Framework of a Circular Bio-economy Model for a Sustainable Leather Industry in Developing Countries

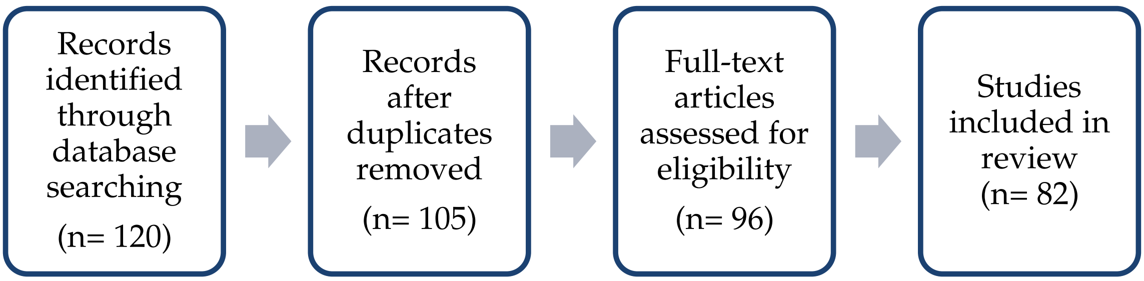

Figure 2. PRISMA flow diagram of the literature search and study selection process. A total of 120 records were identified through database searching. After removing duplicates (n = 105),

MATERIALS AND METHODS

This paper uses a descriptive approach through a literature review of various national and international scientific sources relevant to the theme of environmentally friendly tanning and the utilization of livestock by-products. Data sources include reputable journal articles, research reports, and government publications. The literature search was conducted on Scopus, ScienceDirect, SpringerLink, and Google Scholar databases using the keywords “cleaner tanning,” “livestock hides,” “sustainable leather production,” “enzymatic tanning,” and “circular bioeconomy”. The study selection process was conducted following the PRISMA guidelines, as illustrated in Figure 2. Through successive stages of identification, screening, and eligibility assessment, 96 relevant studies were finally included in the descriptive literature review.

RESULT AND DISCUSSION

1. Animal Hides: Source, Composition, and Sustainability Considerations

Leather is a high-value by-product of the cattle, goat, and sheep farming industries. The tanning process transforms raw hides into high-value products. Animal hides are composed of collagen, elastin, keratin in the hair, as well as fat and water. The collagen content of animal hides reaches 30-35% of dry weight and has a triple helix structure that forms the basis of cross-linking in the tanning process (Covington & Wise, 2019). From a sustainability perspective, the handling and preservation of raw hides represent a critical upstream stage influencing the overall environmental footprint of the leather value chain. Conventional preservation techniques such as salting and air drying are effective in preventing microbial degradation but generate wastewater with high total dissolved solids and chloride concentrations, complicating downstream effluent treatment (Humayra *et al.,* 2023; Rai *et al.,* 2025). In line with the principles of cleaner production, various alternative preservation strategies (such as low-salt methods, cold storage, and enzyme assisted curing) have been developed to reduce dependence on salt and lower the biochemical oxygen demand (BOD) in liquid waste (Kanagaraj *et al.,* 2006; Saran *et al.,* 2013).

Integrating hide utilization within circular livestock farming systems further enhances resource efficiency by linking upstream livestock production with downstream leather processing. Solid and liquid wastes from tanneries can be valorized into biogas, biofertilizers, or animal feed, while organic residues from livestock and agroindustrial activities can serve as substrates for enzyme or bio-based tanning agent production (Devi *et al.,* 2023; Sathish *et al.,* 2019). This systemic integration establishes closed-loop material flows that align leather production with circular bioeconomy principles.

2. Common Leather Tanning Methods

Several tanning methods are widely applied in the leather industry, although their sustainability performance varies considerably. These conventional practices highlight the need for a transition from linear processing maudels toward circular bioeconomy based systems. The use of chromium salts is one of the commonly used tanning methods in the leather tanning industry due to its high versatility, most efficient and affordable in producing quality leather (China *et al.,* 2020; Sabatini *et al.,* 2023). However, this method poses significant environmental and health risks. Trivalent chromium (Cr^{3+}), used during tanning, can be oxidized to hexavalent chromium (Cr^{6+}) under certain conditions. Cr^{6+} is highly carcinogenic and poses serious ecological and human health hazards (Ma *et al.,* 2025; Monga *et al.,* 2022). Chrome tanning materials have a low utilization rate (60-70%) and the potential risk of oxidation of Cr^{3+} to Cr^{6+} in chromium may make it a bygone material (Fan *et al.,* 2025).

Vegetable tanning offers a bio based alternative by employing plant-derived tannins to stabilize collagen fibers. Tannins are polyphenolic secondary metabolites capable of forming hydrogen bonds with proteins, thereby transforming raw hides into durable leather (Auad *et al.,* 2020; Grasel & Ferrão, 2016; Herminiwati *et al.,* 2015). Despite its renewable origin, vegetable tanning is still associated with high organic loads in effluents, indicating that bio based inputs alone do not guarantee environmental compatibility without process optimization.

Combination tanning systems have emerged as an intermediate approach to balance performance and environmental considerations. These systems integrate vegetable tannins with synthetic or semi-synthetic agents such as oxazolidine, producing leather with acceptable mechanical strength and organoleptic properties while reducing reliance on chromium (Musa & Gasmelseed, 2013; tal., 2006; Saran *et al.,* 2013).

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3. Environmental Burden of Conventional Leather Tanning

Traditionally, the tanning industry has operated under a linear "take–make–dispose" paradigm, resulting in high resource consumption and significant pollution. Large volumes of water and chemicals are required throughout processing, generating effluents with elevated BOD, COD, heavy metals, and organic contaminants (Humayra *et al.,* 2023; Sathish *et al.,* 2019). On average, post-tanning formulations consume approximately 360.2 kg of chemicals per ton of finished leather, underscoring the intensity of material use (Hansen *et al.,* 2021).

Chrome tanning exemplifies the limitations of linear processing. Only about half of the applied chromium is absorbed by the hide, with the remainder discharged into wastewater (Sawalha *et al.,* 2019; Susanto & Juhana, 2023). Conventional physico-chemical effluent treatment methods are often ineffective or economically burdensome, particularly due to sludge generation and chromium persistence across a wide pH range (Gizaw *et al.,* 2024). Similarly, vegetable tanning effluents contain recalcitrant polyphenolic compounds that contribute to high COD values and pose challenges for biodegradation (Kanth *et al.,* 2009; Balakrishnan *et al.,* 2020). These limitations collectively demonstrate the incompatibility of linear tanning practices with long term environmental sustainability.

4. Cleaner Leather Tanning within the Circular Bio-economy Framework

The circular bioeconomy framework provides a systems level approach to addressing the environmental challenges of leather tanning by emphasizing resource efficiency, waste valorization, and the use of renewable inputs. Rather than treating waste as an unavoidable output, this framework promotes its reintegration into productive cycles. To move beyond descriptive reporting and to assess the practical relevance of cleaner tanning strategies, a comparative evaluation of alternative tanning technologies is necessary to understand their relative environmental performance, processing efficiency, and technological readiness.

While enzymatic, vegetable, and other bio-based tanning approaches are all positioned as cleaner alternatives to conventional chrome tanning, their performance and maturity differ substantially. Enzymatic processes primarily function as process enablers rather than stand-alone tanning agents. Several studies report that enzymatic soaking and unhairing can reduce sulfide usage by up to 60–80% and decrease wastewater biochemical oxygen demand (BOD) and chemical oxygen demand (COD) by approximately 30–50% compared to conventional lime–sulfide systems, while maintaining acceptable leather softness and grain integrity. Enzymatic-assisted treatments have also been shown to shorten processing time and improve dye uptake efficiency during post-tanning, contributing to lower overall chemical consumption.

Vegetable tanning directly replaces chromium-based agents and therefore eliminates heavy metal discharge, representing a significant environmental advantage. However, this benefit is partly offset by high organic loads in vegetable tanning effluents due to residual polyphenolic compounds, which often result in elevated COD values and longer processing times. Although vegetable-tanned leather generally exhibits good fullness and durability, penetration limitations and lower productivity remain challenges. Emerging bio-based and polysaccharide tanning systems aim to bridge this gap by combining chrome-free chemistry with improved leather performance. Laboratory scale studies report promising gains in hydrothermal stability and mechanical strength, yet most of these systems remain at pilot or experimental stages, with limited data on long-term performance, cost efficiency, and large-scale industrial implementation. Overall, cleaner tanning technologies involve inherent trade-offs between environmental benefits, processing efficiency, and technological readiness, underscoring the need for context-specific integration within a circular bioeconomy framework.

Within this context, plant-derived tanning agents and polysaccharides represent renewable biomass feedstocks capable of substituting hazardous mineral-based chemicals. Their interaction with collagen fibers through hydrogen bonding and cross-linking enhances leather stability while reducing toxic emissions. Nevertheless, variability in raw material composition and extract purity necessitates careful control of processing parameters to ensure consistent tanning performance (Das *et al.,* 2020). Beyond traditional tannins, emerging bio-based agents derived from agricultural and food-processing residues further demonstrate how non-traditional biomass streams can be converted into functional tanning materials, strengthening closed-loop integration by linking agricultural waste management with industrial leather production.

5. Sources of Vegetable and Polysaccharide Tanning Agents within the Framework of Circular Bio-economy

One of the main pillars in the circular bioeconomy model for the leather tanning industry (Figure 1) is the substitution of synthetic chemicals with inputs derived from renewable and waste-based resources. In this context, tannins and plant polysaccharides play a critical role as environmentally friendly alternative tanning agents. The utilization of these materials directly embodies the "Renewable Biomass Raw Materials" and "Agro-industrial Waste" components of the proposed framework. This subsection operationalizes the circular bioeconomy framework by presenting concrete examples of renewable and waste-derived tanning agent sources applicable to leather processing. Table 1. summarizes representative plant-based tannin sources that demonstrate the potential for resource circularity and local biomass valorization.

The circular bioeconomy framework provides a systems-level approach to addressing the environmental challenges of leather tanning by emphasizing resource efficiency, waste valorization, and the use of renewable inputs

In addition, the utilization of polysaccharides from agro-industrial waste is an example of the application of a more advanced circular model. Table 2 highlights this potential, where sources such as corn cobs can be processed into epoxy tanning agents. The utilization of this agricultural waste directly embodies the "Agro-industrial Waste" component in the circular bio-economy framework, transforming previously low-value waste into functional inputs for the tanning process. This approach significantly improves resource efficiency and reduces the waste burden on the environment.

6. Enzymatic Processes as Enablers of a Circular Bioeconomy in Leather Manufacturing

Enzymatic processes primarily function as process enablers by improving process efficiency and reducing chemical inputs during pre-tanning stages. Previous studies have reported that enzymatic-assisted pre-tanning processes can reduce sulfide consumption by approximately 30–70%, while decreasing BOD and COD loads by around 20–50% compared with conventional lime–sulfide systems (Thanikaivelan *et al.,* 2004; Covington, 2009). These quantitative improvements highlight the potential role of enzymatic technologies in supporting cleaner leather processing within a circular bioeconomy framework. In addition, many industrial enzymes can be produced via microbial fermentation using renewable biomass or agro-industrial residues, strengthening waste to resource pathways within a circular bioeconomy.

Table 1. Examples of plant-based tanning sources

Plant source (Common name)	Key compound	Finding	References
Acacia mearnsii (Black Wattle)	Condensed tannins	Widely used commercially; high resistance to detannage	(Auad *et al.,* 2020; China *et al.,* 2020)
Schinopsis lorentzii (Quebracho)	Condensed tannins	Widely used commercially; for heavy leather production	(Auad *et al.,* 2020)
Castanea sativa (Chestnut); *Caesalpinia spinosa* (Tara); *Terminalia chebula* (Myrobalan)	Hydrolysable Tannins	Widely used commercially	(Auad *et al.,* 2020)
Acacia auriculiformis and *A. mangium*	Tannins	Meets Indonesian standards (SNI) when tanned at alkaline pH (8)	(Mutiar *et al.,* 2019; Mutiar *et al.,* 2024)
A. nilotica (Gum Arabic Tree)	Tannins	Potential alternative tanning agent	(Fatema-Tuj-Zohra *et al.,* 2023)
Cassia singueana	Tannins	Derived from stem bark extract	(Teklemedhin *et al.,* 2023)
Pontederia crassipes (Water Hyacinth)	Tannins	Potential alternative tanning agent	(Mustafa *et al.,* 2024; Teklemedhin *et al.,* 2023)
Rumex abyssinicus (Mekmeko)	Tannins	Traditional Ethiopian plant material	(Mohammed *et al.,* 2016)
Uncaria gambir (Gambir)	Tannins	Fuses quickly with skin proteins	(Nirmalawati *et al.,* 2025)
Xylocarpus granatum (Cannonball Mangrove)	Tannins	Potential alternative tanning agent	(Das *et al.,* 2022)
Indigofera sp.	Dye-containing compounds	Can simultaneously tan and color fish skin	(Kusumawati *et al.,* 2016)

Table 2. Examples of Polysaccharide-Based Tanning Agents

Source	Key compound	Finding	References
Snow Fungus (Tremella fuciformis)	Tremella Polysaccharide	Potential tanning agent based on shrinkage temperature analysis	(Wang *et al.,* 2022)
Corn Cob	Epoxidized Polysaccharide	An effective and environmentally friendly tanning agent	(Yin *et al.,* 2025)

At the process level, enzymes have been applied across multiple stages of leather processing. During **soaking**, multi-enzymatic systems containing amylases and lipases facilitate the removal of glycoproteins and residual fats, improving fiber opening and accelerating chemical penetration (Contesini *et al.,* 2018; Pradeep *et al.,* 2021). This is in line with the "Agro-industrial Waste" component of the circular model, in which agricultural waste is converted into functional biocatalysts. In **unhairing**, proteolytic and keratinolytic enzymes selectively hydrolyze keratin, offering a safer alternative to lime–sulfide systems and significantly reducing sulfide contamination in tannery effluents (Fang *et al.,* 2017; Goudarzi *et al.,* 2011). **Bating** employs proteases to remove non collagenous proteins, thereby enhancing softness and grain quality. Although trypsin has historically been used for this purpose and represents an early example of valorizing livestock by products, current trends favor microbial proteases due to their higher stability, purity, and scalability (Cao *et al.,* 2020; Lyu *et al.,* 2017). In **degreasing**, synergistic combinations of lipases and proteases promote efficient fat removal through concurrent lipolysis, proteolysis, and emulsification (Bharagava & Mishra, 2018). Like proteases, these enzymes can be produced through microbial fermentation that utilizes side streams from the agricultural industry, demonstrating how circular models can be consistently applied across various stages of the process. Finally, in **post-tanning and dyeing**, enzymatic treatments can enhance dye uptake and uniformity, enabling more intense and consistent coloration while reducing dye and auxiliary chemical usage (Tasca & Puccini, 2019; Lasoń-Rydel *et al.,* 2024).

Despite these advantages, the large scale adoption of enzymatic processes faces several limitations that warrant critical consideration. Enzymes are often associated with higher upfront costs compared to conventional chemicals, and their activity can be sensitive to variations in pH, temperature, and substrate composition, requiring tighter process control. From an industrial perspective, scalability remains a challenge, particularly for small and medium-sized enterprises (SMEs), which may lack the technical capacity and capital investment needed to implement enzyme-based systems consistently. In addition, the performance of enzymes can vary depending on raw hide quality and processing conditions, sometimes necessitating hybrid approaches that combine reduced chemical dosages with enzymatic treatments rather than complete substitution.

Consequently, while enzymatic technologies represent a cornerstone of circular bioeconomy-oriented leather manufacturing, their role should be viewed as part of an integrated transition strategy rather than a standalone solution. Future research and industrial implementation should focus on improving enzyme robustness, reducing production costs through optimized fermentation using low-value biomass, and developing flexible processing schemes that facilitate adoption across diverse tannery scales. Such advances would enhance the practical feasibility of enzymatic processes and strengthen their contribution to circular and sustainable leather value chains.

7. Enzyme Sources as Implementation of the Circular Bioeconomy Model

The implementation of the Circular Bioeconomy Model (Figure 1) is highly dependent on the use of environmentally friendly technologies, and enzymatic processes are a prime example. Enzymes, particularly proteases and keratinases, offer biodegradable alternatives that can replace harsh conventional chemicals in the pre-tanning process stages, thereby reducing hazardous waste and promoting clean production. These diverse enzyme sources can be directly integrated into the proposed circular framework through two complementary pathways. On the one hand, the use of enzymes promotes waste valorization, transforming materials that were previously considered pollutants into valuable inputs. A concrete example of this is the use of protease from the bacterium *Vibrio metschnikovii*, isolated from fishery waste, which directly embodies the 'Fishery/Livestock Waste' component in the model. Similar approaches, such as the isolation of Bacillus safensis from tanning waste itself, even show the potential to create closed-loop circular systems within the industry.

On the other hand, this approach is also in line with the fundamental principle of bio-economics, namely the utilization of renewable resources. This is realized by extracting enzymes from abundant biological sources, such as microbes (*Bacillus subtilis*, *Aspergillus flavus*) and plants (for example, papain from papaya and zingibain from ginger). Thus, these two pathways synergistically support the shift from conventional chemical inputs to sustainable and renewable alternatives. Table 3 below provides a detailed overview of these various enzymatic sources, each of which has the potential to support the realization of a more sustainable and circular leather industry.

8. Material and Technology Innovations to Support the Circular Model

To realize an effective Circular Bioeconomy Model (Figure 1), innovation is needed not only in the main tanning agents but also in combination materials and process technologies. The goal is to improve product quality while drastically reducing environmental side effects, which is at the heart of the circular economy. This approach is realized through several key strategies. First, improving product quality from renewable sources. Leather tanned with vegetable agents often exhibits low hydrothermal stability due to insufficient cross-linking with collagen tissue. To address this, initial innovations focused on combination tanning systems. For example, pairing vegetable tannins with agents like oxazolidine, zinc, or aluminum improves stability (Musa & Rao, 2011) Similarly, combining dialdehyde and mimosa tannins has been shown to significantly increase tensile strength to 245.71 kg/cm^2, tear strength to 44.63 kg/cm, and elongation at break to 45.23% (Bastanian *et al.,* 2025)

Second, waste valorization and chrome-free alternatives. More recent developments have been largely driven by the goal of creating environmentally friendly processes that reduce pollutants. The main focus in this trend is the development of chrome-free tanning alternatives.

Table 3. Examples of Enzymatic Sources for Leather Processing

Enzyme/source organism	Origin	Primary function/description	References
Microbial sources			
Bacillus subtilis	Bacteria	Dehairing (Keratinase)	(Arunachalam & Saritha, 2009; Sanghvi *et al.,* 2016)
B. velezensis	Bacteria	Dehairing	(Khan *et al.,* 2024)
Bacillus safensis	Bacteria	Isolated from tannery waste	(Nachimuthu *et al.,* 2022)
Brevibacillus agri	Bacteria	Protease & Keratinase production	(Agustien *et al.,* 2015)
Paenibacillus woosongensis	Bacteria	Keratinase production	(Paul *et al.,* 2013)
Vibrio metschnikovii	Bacteria	Protease production (from fish waste)	(George *et al.,* 2014; Saranya *et al.,* 2016)
Aspergillus flavus	Fungi	Dehairing	(Ugbede *et al.,* 2023)
Aureobasidium pullulans	Yeast	Protease production	(Chi *et al.,* 2007)
Plant sources			
Cysteine Protease	Plant	From lentils, green gram, peas	(Shaha *et al.,* 2013)
Papain (from Papaya) and *Zingibain* (from Ginger)	Plant	Keratin & Gelatin hydrolysis	(Troncoso *et al.,* 2022; Santika *et al.,* 2014)
Sulfihydryl Protease	Plant	From frangipani (*Plumeria obtusa*) stems	(Laksanawati *et al.,* 2022)

Innovations in this category include chrome free combination systems based on chestnut and tetrakis (hydroxymethyl) phosphonium sulfate (THPS) (Girmay *et al.,* 2024) as well as multifunctional tanning agents based on chitosan derived from discarded enoki mushroom roots (Liang *et al.,* 2024) Advancing the use of biomass, the chitosan oligomer COS-GTE has been proposed not only to address chromium contamination but also to impart unique antimicrobial properties to leather (Liang *et al.,* 2023)

Third, process efficiency and pollutant reduction. Beyond direct tanning agents, technological advances are being applied throughout the leather production workflow to improve sustainability and efficiency. Nanotechnology, for example, is used to reduce chemical consumption, such as with ZPIL-modified MCM-48 nanoparticles that reduce the Cr2O3 content in tanning liquids by up to 28.8% (Sun *et al.,* 2025) and with water soluble chitosan based CuO-GO nanocomposites (Rahman *et al.,* 2025). Process-based improvements include ultrasonic-assisted chrome tanning, which shortens processing time and reduces chrome dosage (Mengistie *et al.,* 2016). Innovations also extend to other stages, such as using a mixture of protease and ammonium salts for optimized fur tanning (Covington & Wise, 2019) and applying cellulose derivatives such as nitrocellulose for leather finishing (Tamilselvi *et al.,* 2019).

9. Processing Tanning Agents for Industry within the Framework of Circular Bio-economy

The development of plant-based tanning agents for industry, from raw materials to finished products, can be effectively integrated into the Circular Bioeconomy Model (Figure 1). This process consists of three main stages: raw material preparation, active compound extraction, and extract purification, each of which plays an important role in creating a sustainable and value-added production cycle.

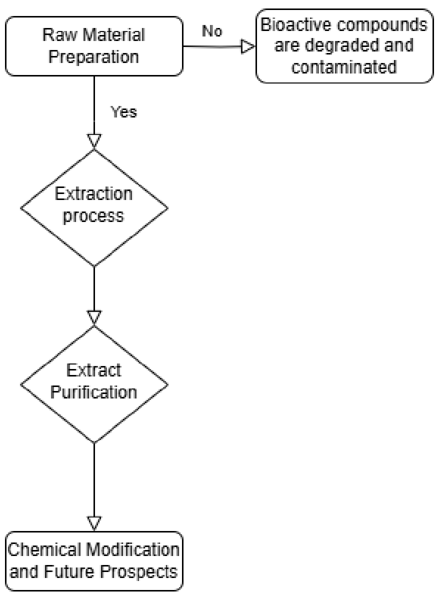

Figure 3. Flowchart of the Vegetable Tannin Production Process

9.1 Raw Material Preparation

The first and most critical stage is the preparation of raw materials. As shown in Figure 3, successful preparation (“Yes” path) is essential. This stage is the embodiment of the “Biomass Resource Utilization” component in the circular bioeconomy framework. The correct preparation of the material for extraction is as important as the selection of the extraction method. This step aims to prevent the degradation of bioactive compounds as well as the development of mold and bacteria (Krakowska-Sieprawska *et al.,* 2022), which is the outcome of the “No” path in the diagram. By ensuring that the raw materials are maintained in good quality, we secure valuable inputs for further processing, while minimizing potential waste from the outset of the process.

9.2 Extraction Process and Extract Purification

Extraction serves as the primary valorization step, converting prepared biomass into concentrated tannin extracts. The adoption of green extraction technologies, such as microwave- and ultrasonic-assisted methods, improves diffusion efficiency and tannin uptake while reducing energy and solvent use (Sivakumar *et al.,* 2014; Mutiar *et al.,* 2024). Subsequent purification enhances product quality and reduces organic pollutant discharge, enabling the production of lighter-colored vegetable-tanned leather with lower environmental impact (Conca *et al.,* 2024). This dual benefit directly supports circular objectives of waste minimization and value enhancement.

Beyond the performance of individual cleaner tanning technologies, their sustainability contribution should be evaluated within an integrated circular livestock-based bioeconomy perspective. Within a circular livestock-based bioeconomy, cleaner tanning technologies can be integrated through interconnected material and waste flows. For instance, enzymatic agents derived from agricultural biomass or livestock by-products can be utilized in pre-tanning stages to reduce chemical consumption, while solid residues from hide processing may serve as substrates for microbial or enzymatic production. Treated tannery effluents can further be reused for non-critical processing steps, thereby reducing freshwater demand and minimizing waste discharge across the livestock–leather value chain.

10. Critical Comparison of Enzymatic vs Vegetable vs Other Bio-based Tanning Method

Enzymatic, vegetable, and other bio based tanning approaches are increasingly promoted as cleaner alternatives to conventional chrome tanning; however, their performance, environmental impacts, and levels of technological readiness vary considerably. Enzymatic processes mainly act as process enablers by reducing chemical usage, water consumption, and wastewater load, particularly in pre-tanning and post-tanning stages. Previous studies have reported lower sulfide use, reduced BOD and COD values, and shorter processing times compared with conventional lime–sulfide systems, while maintaining acceptable leather softness and grain quality. Nevertheless, enzymatic treatments cannot function as stand-alone tanning agents and require careful process control.

Vegetable tanning directly substitutes chromium-based agents and utilizes renewable biomass resources. This method produces leather with good body and durability but generally requires longer processing times and generates effluents with relatively high organic loads due to residual polyphenolic compounds. Although these effluents are less hazardous than chromium containing wastes, inadequate wastewater treatment may still result in significant environmental impacts. Recent developments, such as combination tanning systems and refined tannin extracts, have improved penetration efficiency and reduced organic discharge.

Emerging bio-based and polysaccharide tanning agents represent a promising but less mature alternative. These materials show potential in achieving chrome-free tanning with acceptable hydrothermal stability and functional leather properties; however, most applications remain at laboratory or pilot scale. Limitations related to raw material availability, production cost, and limited industrial validation continue to restrict large-scale adoption. Overall, no single cleaner tanning technology can currently be considered a universal solution, and their practical implementation should be selected based on processing goals, environmental considerations, and technological readiness.

10.1 Prospects Through Sustainable and Green Industry

Within the circular bioeconomy framework, future prospects for the leather industry can be conceptualized through interconnected strategies that address process efficiency, material substitution, resource circularity, enabling technologies, and socio-economic readiness.

10.2 Process Optimization of Existing Tanning Technologies.

Optimizing conventional tanning processes represents a pragmatic and scalable pathway toward sustainability. Recent advances, including ultrasonic-assisted chrome tanning and AI-based process optimization, demonstrate substantial reductions in processing time, energy consumption, and chemical inputs while maintaining acceptable leather quality (Zhang & Chen, 2020; Zhang *et al.,* 2024). Although minor trade-offs in chrome distribution or thermal stability have been reported, overall mechanical and organoleptic properties remain comparable to conventional methods. These approaches align with the *Process Optimization* stage of the circular bioeconomy by improving resource efficiency without requiring complete technological replacement, making them particularly relevant for industrial scale adoption.

Transition Toward Chrome-Free and Renewable Tanning Systems. Beyond optimizing existing systems, the gradual transition toward chrome-free tanning agents is central to sustainable leather production. Vegetable tanning contributes directly to the *Renewable Biomass* component of the circular bioeconomy; however, its scalability is increasingly constrained by limited availability of plant-based raw materials, particularly in developing regions such as Indonesia (Dahlia & Sembiring, 2023). To address these limitations, alternative tanning systems based on silicone and biomass-derived materials have emerged as potential chrome-free solutions (Zhang *et al.,* 2024), While such systems offer technical consistency and reduced reliance on chromium, their adoption may be challenged by higher costs and dependence on imported chemicals, especially for SMEs. This highlights the need for context-specific solutions that balance technological performance with local resource availability.

11. Waste and By-product Valorization as Circular Resources

The utilization of waste streams and by-products represents a core strategy for advancing circularity in the leather industry. Agricultural residues, such as rice husk-derived silica, and bio-based oils have been explored as substitutes for conventional finishing and fatliquoring agents, demonstrating cost-effective and environmentally friendly performance (Ebtasam *et al.,* 2025; Susanto & Ajie, 2024; Sahu *et al.,* 2025). In addition to reducing pollution and raw material consumption, these approaches generate added value from previously underutilized resources, directly supporting the *Waste-to-Resource* principle of the circular economy.

12. Limitations and Implementation Challenges

Despite the environmental potential of cleaner and bio-based tanning technologies, **economic feasibility and scalability remain significant barriers** to their widespread adoption in the leather industry. For example, alternative materials such as bacterial-cellulose based leather-like products have been shown to incur production costs of about **USD 97.92 per m^2,** which reflects the high cost of raw biomass integration and processing relative to traditional leather (which ranges from USD 39.7 to USD 220.8 per m^2) (Yang *et al.,* 2024). Many sustainable tanning approaches developed to date are either **not as effective as conventional**

chromium tanning, affect functional properties, or remain cost-prohibitive, limiting their competitiveness without scale-ups or process optimization (Hassan *et al.,* 2023). High processing costs include not only specialized inputs (enzymes, polymers, extraction aids) but also **infrastructure adaptation** for non-chrome processes, which can be prohibitive for smaller tanneries and SMEs that lack capital and technical capacity to absorb these upfront investments. In addition, **availability and consistency of bio-based raw materials** continue to challenge supply chains; many promising agents are still in early stages of industrial development, making reliable sourcing and quality control difficult for large-scale operations (bio-based adoption limitations). Furthermore, market analyses indicate that plant-based tanning substitutes may cost **2–3 times more per kilogram** than conventional tanning agents, underscoring persistent affordability challenges even as demand for eco-friendly options grows, as reported by PmarketResearch (2024). Finally, **regulatory and institutional readiness** varies across regions, with fragmented standards and evolving certification requirements complicating the integration of cleaner technologies into existing industrial systems. Together, these cost and implementation constraints suggest that policy support, collaborative innovation, and scaled-up production pathways are required to enhance economic viability and uptake of sustainable leather tanning within a circular bioeconomy framework.

CONCLUSION

This review reframes sustainable leather production by positioning tanning innovation within an integrated circular bioeconomy that links livestock systems, waste valorization, and cleaner processing technologies. Rather than treating tanning sustainability as an isolated industrial issue, the findings emphasize that livestock management (through efficiency, welfare, and traceability) plays a decisive upstream role in determining hide quality and the environmental footprint of the leather value chain. The synthesis of recent studies indicates that conventional chrome-based tanning remains environmentally burdensome, while vegetable tanning, although eliminating heavy metals, continues to pose environmental challenges due to organic effluent generation. In contrast, enzymatic processes, plant-derived and polysaccharide tanning agents, and hybrid bio-based systems enable a transition toward more resource efficient and lower-impact leather production. When embedded within a circular bioeconomy framework, these approachhes facilitate the valorization of agricultural, fishery, and livestock wastes into value-added tanning inputs, contributing to pollution reduction and enhanced economic resilience.

The key novelty of this review lies in identifying enzymatic and biomass-based tanning technologies as systemic enablers that integrate livestock sustainability with industrial processsing and circular resource flows. Overall, advancing a sustainable leather industry requires a coordinated circular bioeconomy approach capable of delivering both measurable environmental improvements and long-term economic value creation.

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