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Review

Exploring Tannery Solid Wastes as a Source of Animal Feed

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Abstract: This review delves into the processing of tannery solid waste, emphasizing fleshings and chromium-tanned leather waste. This paper centers on fat recovery, chromium elimination, and protein preservation, aiming to make them apt for animal consumption. This paper also assesses the potential of introducing such recycled products to the global market. Drawing on the literature from the past two decades, sourced comprehensively from Scopus and Web of Science, 36 articles were selected because of their significant contributions from leather production powerhouses such as India and Brazil. Fleshings have shown immense potential as animal feed, and the extraction of tallow and collagen from rawhide trimmings yields up to 98% and 93%, respectively. Fermented tannery fleshings, notably with Enterococcus faecium HAB01, also demonstrate strong antioxidant capabilities. The overarching consensus emphasizes the need for rigorous purification when dealing with chromium-containing wastes, addressing concerns tied to Cr (III) and Cr (VI). Furthermore, raw tannery fleshings stand out as a sustainable, cost-effective, and globally marketable solution for animal feed production.

Keywords: leather waste; animal feed; wet blue recycling; global trade

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1. Introduction

The animal food industry boasted a remarkable global trade value of USD 40.9 billion in 2021. Out of 1217 traded products, it secured the 110th spot, meaning that animal food represents a commanding presence, accounting for the top 9% of all traded commodities. From 2020 to 2021, the export value of animal food surged by 17.8%, rising from USD 34.7 billion to USD 40.9 billion. Such a significant increase, almost 18% within a year, underscores a mounting demand for animal food [1]. This surge might be attributed to factors such as an expansion in animal farming and a global uptick in pet ownership. In 2021, the top five leading animal food exporters were Germany (USD 4.43 billion), the Netherlands (USD 3.92 billion), the United States (USD 3.81 billion), France (USD 3.29 billion), and China (USD 2.53 billion). On the import side were countries such as Germany (USD 3.19 billion), the United States (USD 2.55 billion), France (USD 1.9 billion), the Netherlands (USD 1.83 billion), and Poland (USD 1.6 billion). Interestingly, there is a noticeable overlap between top importers and exporters [2]. This overlap hints at the intricate dynamics of the supply chain in this industry. It is worth noting that the industry has an accumulated value of USD 35.7 billion. Recognizing the potential, the sector has innovatively incorporated nutrient-rich waste materials to devise enhanced fattening and growth formulas [3–6].

While the leading animal exporters dominate discussions due to their significant contributions, it is essential to recognize the broader spectrum of worldwide production. In 2019, global layer feed production experienced a 4% growth, with Asia–Pacific leading at 7%, possibly due to the African swine fever crisis prompting increased egg production. In contrast, the Middle East saw an 11% decline, likely influenced by geopolitical tensions. Broiler feed production is equivalent to 10 million metric tons from the previous year. Africa and Asia–Pacific both marked a 6% growth, while other regions registered a 2–3% increase. This upward trajectory is expected to continue, driven by escalating protein needs [7]. Meanwhile, North America's ruminant feed production was at 62.3%, and Europe contributed 21.9%. Asia–Pacific dominates in aquaculture feed, holding 30% of the global share, with China, Vietnam, and Bangladesh as major contributors. Additionally, pet feed saw a 4% global growth, especially in regions such as Asia–Pacific, Europe, and Latin America. Countries such as China, Indonesia, Portugal, Hungary, Ecuador, and Argentina were at the forefront of this growth [7,8].

The vast scale of the animal feed industry highlights its dependence on large amounts of both vegetable and animal-derived ingredients [9]. Given the high cost of protein in feed formulas, there is a pressing need to identify more affordable protein sources. One promising solution is the controlled use of edible waste, ensuring the continued quality of animal-derived products [10]. A WWF report about animal feed sources underscores the potential of alternative animal diets, such as those incorporating grocery and bakery waste, as well as black soldier fly larva flour. Their study encourages the integration of waste into animal diets to provide an environmentally friendly alternative to conventional feeds, all while ensuring the safety and well-being of the animals [11].

An estimated 5 billion livestock are earmarked globally for the meat industry and its derivatives [12]. In 2014, global statistics suggested an average meat consumption of 43 kg per person [13]. The meat industry generates large amounts of waste; 46 to 50% of each bovine is waste [14]. Slaughterhouse by-products, such as hides—which comprise 4 to 11% of live cattle weight—find their way to the tanning industry [15]. As reported by the FAO, by 2015, out of the 5,924,823,536 kg of processed raw hides worldwide, 506,662,677 kg were transformed into leather [16]. The tanning industries utilize part of the hides from slaughterhouses and convert these animal hides into leather, enhancing their utility for various products [17]. Yet, per Buljan and Ludvik [18], for every 1000 kg of wet salted hides, only 255 kg emerges as finished leather, turning 75% into waste. The tannery waste includes fleshings, hair, tails, masks, shavings from splitting, dust from buffing wet blue, and highly contaminated liquid effluents [19,20]. Among all these wastes, fleshings and shavings, and the buffing of the wet blue are being recycled to produce animal feed [21] and other valuable products such as carbon sources for steel production [22], adsorbents [23,24], adhesives [25], synthetic leather [26], biodiesel, bioplastics [27], fertilizers [28–30], elastin [31], among others [32].

This review paper aims to delve into the recycling processes of tannery solid waste, explicitly focusing on transforming fleshings and chromium-tanned leather waste into safe and nutritious animal feed. The primary objective is to identify and evaluate the most efficient processing techniques that ensure fat recovery and chromium removal while preserving the protein content, making the resulting products suitable for animal consumption. Furthermore, this work seeks to determine the feasibility of introducing these recycled products into the global market, thereby providing a sustainable solution to tannery waste management and contributing to the animal feed industry.

2. Methodology

An extensive literature review was conducted to comprehensively examine the potential use of tannery waste for animal feed production.

2.1. Data Collection

Database and Search Criteria:

Scopus: The initial literature search was conducted on Scopus, targeting the utilization of tannery wastes as feed sources. The specific keywords employed for this search were "tannery", "wastes", and "feed".

Web of Science: A supplementary search was carried out on Web of Science using a combination of keywords "tannery", "wastes", "animal", and "feed".

Time Frame: The review spanned the literature from the past two decades, resulting in a preliminary collection of 149 documents.

Geographical Distribution: Out of these, the major contributors were India (68 publications), Spain (11 publications), Bangladesh (12 publications), and Brazil (11 publications). The dominance of these countries can be attributed to their significant leather production activities.

Publications per year: Scopus database records since 2004 show a consistent annual publication rate of six to ten papers on tannery waste utilization for animal feed, highlighting a lack of research in this area attributed to manufacturers' dominance in waste management, limiting broader exploration. Proprietary issues lead to undisclosed conversion processes, potentially obstructing academic advancement; see Figure 1 for visual representation.

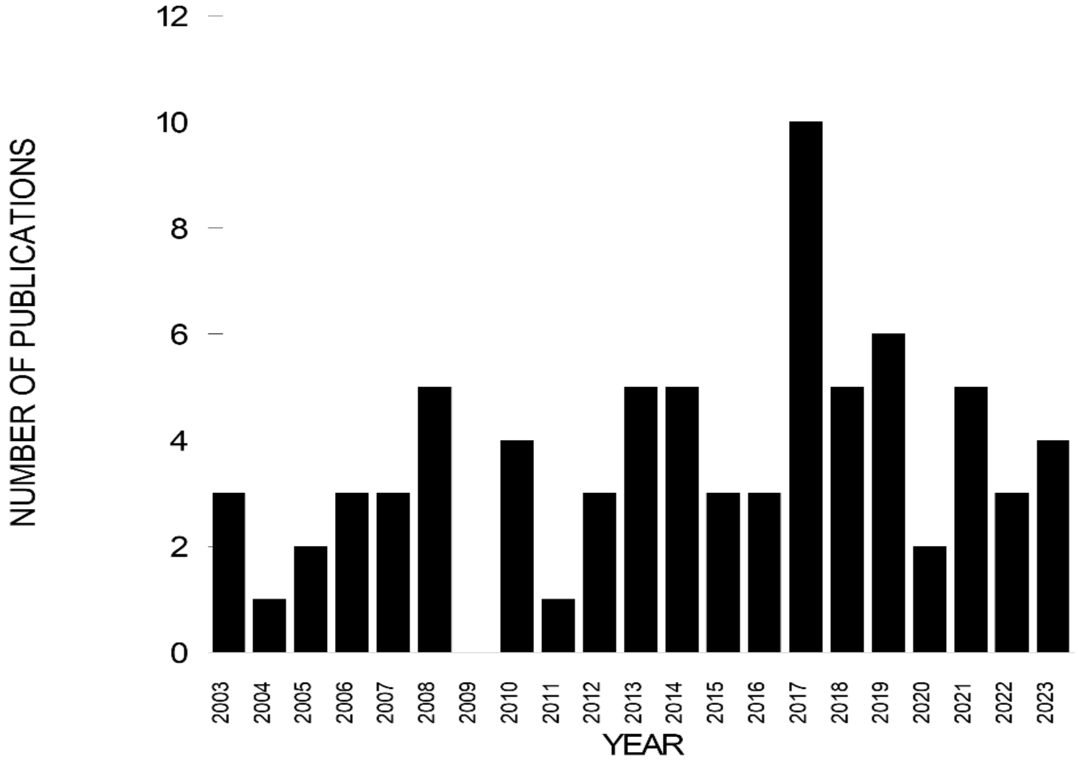

Figure 1. Publications about tannery waste used for animal feed in the past 20 years reported in Scopus.

2.2. Analysis of Literature

Using the Connected Papers software tool, the literature from the past decade was further dissected into three main topics:

Solid Tannery Waste: The literature focused on solid tannery waste recycling into animal feed. Keywords "animal feed", "tannery waste", and "recycling" yielded 41 articles (Figure 2A).

Wet Blue Products: The literature that explored products derived from wet blue with keywords "wet blue" and "recycling", yielding 38 articles (Figure 2B).

Tannery-Derived Tallow: The literature that investigated the extraction of products with the terms "beef tallow" and "tanneries". This search resulted in 41 articles (Figure 2C).

The Boolean operator "AND" was used for all searches to narrow down results. The Connected Papers tool visualized the search results with each publication represented as a node; the node's size correlates with its citation frequency. Furthermore, content-similarity-based connections were made evident through linking lines.

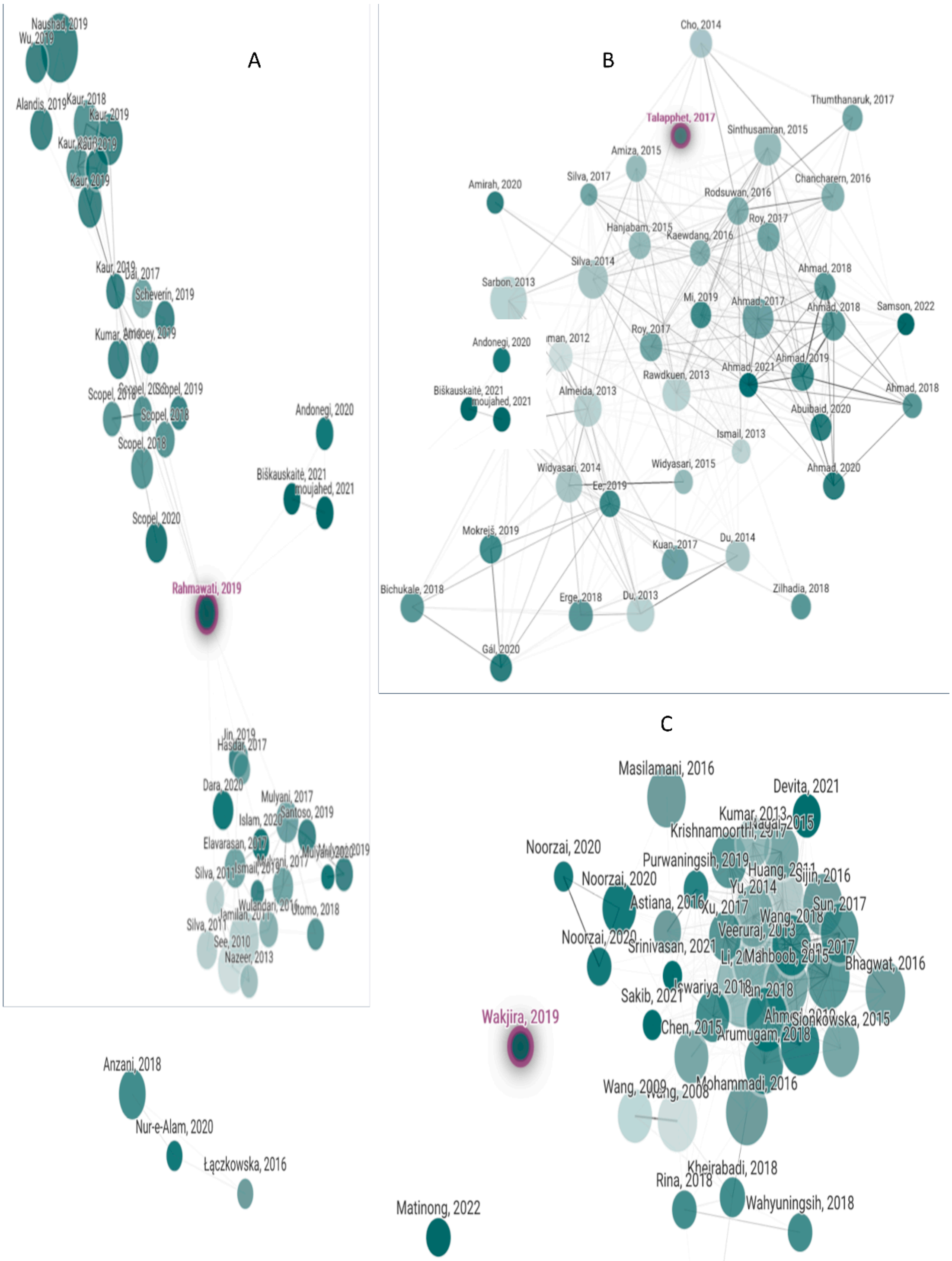

Figure 2. Representation of key research articles on solid tannery waste recycling for animal feed production. The figure visualizes pivotal papers as interconnected nodes, each signifying its relevance in the field: (**A**) results from the search terms "tannery waste AND recycling", (**B**) derived using "wet blue AND recycling", (**C**) based on the words "beef tallow AND tanneries". Each node represents an article, and the interconnections hint at related research or shared citations. Source: connected papers (accessed on 29 August 2023).

Supplementary Search: Google Scholar was subsequently leveraged to fetch specific statistical data and additional information related to the topic.

2.3. Selection and Filtering Process

After data retrieval, a meticulous selection procedure was initiated. Duplicate entries identified across the different searches were excluded. After this refinement, 36 articles with the same focus that our investigation had were selected as foundational references for this review, as outlined in Table 1, and the rest of the articles were not completely related to the topic.

Table 1. Classification of research articles based on the investigated topics.

	Title of the Article	Topic
1	Use of tannery wastes in the diet of broiler	Feed
2	Protein recovery from tannery fleshings using proteases of chicken intestines for the animal feed industry	Recycling
3	Systems for chromium recirculation in tanneries	Recycling
4	Chromium poisoning in rats feeding on tannery residues	Toxicity
5	Current trends in solid tannery waste management	Recycling
6	Toxicity study in mice fed with corn produced in soil containing tannery sludge vermicompost and irrigated with domestic wastewater	Toxicity
7	Alternative protein sources in sea bass nutrition	Feed
8	Chromium contents linked to iron oxide at areas with tannery sludge disposal	Recycling
9	Enhanced production of *Aspergillus tamarii* lipase for recovery of fat from tannery fleshings	Animal
10	Poultry feed based on protein hydrolysate derived from chrome-tanned leather solid waste: creating value from waste	Toxicity
11	Effects of Leather Industry on Health and Recommendations for Improving the Situation in Pakistan	Toxicity
12	Genotoxicity of industrial solid waste leachates in *Drosophila metanogaster*	Toxicity
13	An illustrative application of a prototype approach to evaluation of waste management options for the leather manufacturing industry	Recycling
14	In vitro antioxidant and antibacterial properties of hydrolyzed proteins of delimed tannery fleshings: comparison of acid hydrolysis and fermentation methods	Recycling
15	Trace elements concentration in soil and plant within the vicinity of abandoned tanning sites in Bangladesh: an integrated chemometric approach for health risk assessment	Toxicity
16	An imaginary journey to the collagen molecule for a better understanding of leather waste treatments	Recycling
17	Histopathological changes studied in the liver and kidney of quail due to manifested by the different levels of chrome shaving replacing animal protein in the feed.	Toxicity
18	Production and potential uses of co-products from solid tannery waste	Recycling
19	Chromium recycling of tannery waste through microbial fermentation	Recycling
20	Hydrolysis of tannery wastes to protein meal for animal feedstuffs: A process and product evaluation	Feed
21	Processing of leather waste: Pilot scale studies on chrome shavings. Isolation of potentially valuable protein products and chromium	Feed
22	Chromium from tannery waste in poultry feed: A potential cradle to transport human food chain	Feed
23	Studies on recovery of chromium from tannery wastewater by Reverse Osmosis	Recycling
24	Leather solid waste: An eco-benign raw material for leather chemical preparation—A circular economy example	Recycling
25	Mathematical modeling and experimental studies on biochemical conversion of Cr (VI) of tannery effluent to Cr (III) in a chemostat	Feed
26	Microbial sorption studies for removal of trivalent chromium from model tanning bath	Recycling
27	Removal of organics and nutrients from tannery effluent by advanced integrated wastewater pond systems® technology	Feed
28	Total control of chromium in tanneries—thermal decomposition of filtration cake from enzymatic hydrolysis of chrome shavings	Recycling
29	Utilization of tannery fleshings: Optimization of conditions for fermenting delimed tannery fleshings using Enterococcus faecium HAB01 by response surface methodology	Feed
30	Development of simultaneous partial nitrification, anammox and denitrification (SNAD) in a non-aerated SBR	Recycling

Table 1. *Cont.*

	Title of the Article	Topic
31	Utilization of Solid Wastes from Tanneries as Possible Protein Source for Feed Applications: Acute and Sub-Acute Toxicological Studies to Assess Safety of Products Prepared from Delimed Tannery Fleshings	Feed
32	Optimization of organic load for co-digestion of tannery solid waste in semi-continuous mode of operation	Recycling
33	Histopathological changes observed in the heart and gizzard of quail chicks Coturnix Coturnix japonica administrated by the different levels of chrome shaving	Feed
34	Chromium (Cr) Contamination of Poultry from Use of Tannery-Based Cr-Contaminated Feed Ingredients and Public Health and Environmental Risks	Feed
35	Removal of trivalent chromium contaminant from aqueous media using FAU-type zeolite membranes	Recycling
36	Biotransformation of bovine tannery fleshing into utilizable product with multi functionalities	Feed

3. Results

3.1. Solid Waste Tannery Residues

The leather production process generates a diverse array of wastes, each with its unique characteristics and potential environmental ramifications, as detailed in Table 2. Approximately 80% of these wastes are residues from unutilized hides, encompassing tanned solid byproducts such as hair, cow tails, raw hides, fleshings, and hide trimmings. Many of these residues find utility in gelatin factories or are repurposed into distinctive products such as pet toys, fertilizers, collagen, and keratin [33]. Shavings, although collagen-rich, are tainted with chrome. Yet, they hold promise in collagen manufacturing, adhesive production [34,35] and as fillers in composite materials [36].

Liquid wastes pose significant challenges, both in terms of volume—with 50,000 L required to produce just 1 kg of leather [37], and composition, laden with heavy metals [38], sulfides [39] and organic matter. The tanning stage introduces tanning liquors, the composition of which varies with the tanning technique and includes substances such as tannins and chromium salts [40]. Historically, the focus was on lowering the contaminants in wastewater before releasing them back into the environment. However, modern industries recirculate wastewater, aiming to curtail water usage and, finally, decontamination processes [41].

Gaseous emissions are another concern. Compounds such as VOCs are emitted throughout the production process, with hydrogen sulfide and ammonia being especially prominent during beam house operations, also in this industry the odor is a mandatory concern to address [42].

Furthermore, sludges, the byproducts of wastewater treatment, comprise a mix of organic and inorganic substances, demanding meticulous disposal to minimize environmental repercussions [37,43]. In summation, the intricate waste landscape of the leather industry emphasizes the imperative for eco-friendly practices and forward-thinking waste management approaches.

Table 2. Synopsis of wastes resulting from different processes during leather tanning.

Type of Waste	Sources and Possible Uses
Solid Wastes	Raw Skin and Hide Trimmings: Cuts of hides and skins are protein-rich and sometimes used in animal feeds or for gelatin production [44,45]. Fleshings: These are the fatty tissues removed from the inner side of hides and skins. They are protein-rich and can be processed to extract oils and proteins [45]. Splitting Waste: Generated during the splitting operation to obtain desired leather thickness, they can be used for making suede or other lower-grade leather products [46]. Shavings: Generated when uniforming the leather or wet blue thickness, they are rich in collagen contaminated with chrome, sometimes used in collagen production or as fillers in composite materials [47].

Table 2. *Cont.*

Type of Waste	Sources and Possible Uses
Liquid Wastes (Effluents)	Soaking Waters: These contain water-soluble proteins, hair, dirt, and dissolved and suspended solids [47] Lime Liquors: Generated as residues from the unhairing process, these liquors contain dissolved hair, lime, and sulfides [20,48,49] Tanning Liquors: Depending on the tanning process (vegetable, mineral, or synthetic), the waste liquors contain tannins, chromium salts, or other agents [20,48,49]. Dyeing and Finishing Effluents: These contain residual dyes, pigments, resins, fats, and other finishing agents [20,48,49].
Chemical Wastes	Chromium Compounds: These are particularly relevant in chrome tanning processes. Chromium can be toxic, especially Cr (VI) and concentrations [50]. Organic Solvents: Solvents used in dyeing and finishing processes [51,52]. Tannins: These residues can be of vegetable or synthetic origin, used in the tanning process [51,52]. Sulfides: Sulfides are used in the dehairing process and can be harmful if released into the environment [39,53]
Gaseous Emissions	Volatile Organic Compounds (VOCs): VOCs are emitted during drying, finishing, and thermal processes [54,55]. Hydrogen Sulfide and Ammonia: Substances released during beam house operations (such as soaking, liming, and unhairing) [54,55].
Sludges	These are by-products of wastewater treatment processes. They contain organic and inorganic materials and need careful handling and disposal [56,57].

3.2. Products for Animal Feed Obtained from Different Solid Tannery Wastes

In the tannery processes, solid wastes primarily derived from raw or tanned cowhide are frequently harnessed to produce animal feed. This inclination can be attributed to their substantial content of fats and proteins, coupled with the ease of procuring materials readily assimilable into animal dietary formulations, as illustrated in Figure 3.

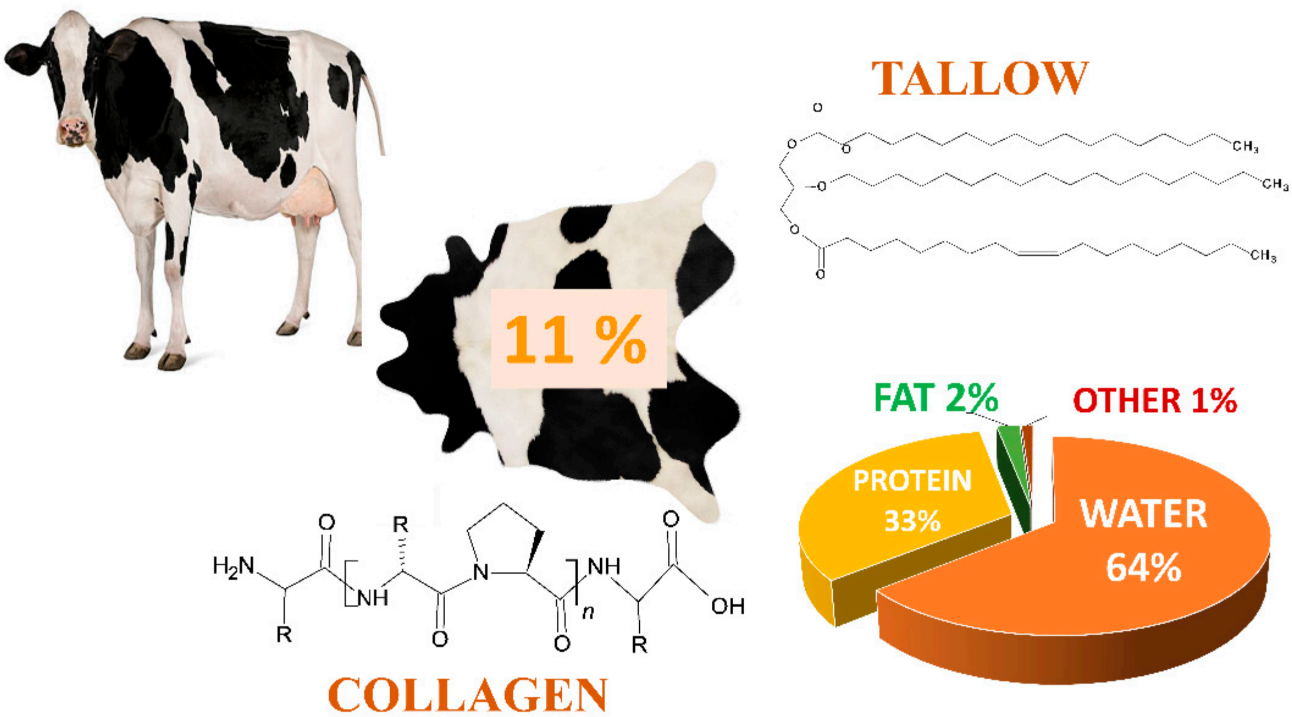

Figure 3. Assessment of cowhide composition and identification of utilizable by-products in the tannery process [58].

3.2.1. Products Derived from the Residual Fleshings of Tanneries

The fleshings, a blend of skin, muscle, and tallow, are mechanically excised from hides to enhance the permeation of chemicals into the skin during the depilation and tanning processes [59]. The surplus skin and the portions not utilized in the tannery are sold to manufacturing units to produce gelatin/collagen [60] and adhesives [61]. Traditionally, meat remnants with tallow are disposed of in landfills. However, current trends are exploring recycling strategies for these wastes. These include their use in biodiesel production [62], hydrogen generation [63], and soap manufacturing [64]. Furthermore, they undergo processing to yield meals enriched with protein and fat, suitable for animal feed [65], as detailed below.

The composition of rawhide trimmings varies from 70.4 to 82.6% of moisture, 5.1 to 7% protein, and 7.3 to 7.8% of fat [66,67]. Various methods, including acid, basic and enzymatic hydrolysis, can extract the proteins in the form of collagen [68]. In the raw trimmings through innovative acid hydrolysis, using mixes of acids, the collagen extraction yields 85% using acetic acid and 93% with propionic acid. This yield discrepancy was further supported by circular dichroism results, which showed that the collagen extracted with propionic acid solution had a higher ellipticity than collagen extracted with acetic acid at 222 nm, a feature indicative of a triple helical structure. The circular dichroism results confirmed that the collagen derived from trimming waste maintained its native triple helical conformation being a collagen of high quality [69].

Tannery fleshings also serve as a collagen source through mechanical defatting and enzymatic hydrolysis using a trio of enzymes such as (A) an alkaline proteolytic enzyme with exo-activity, (B) alkaline proteolytic enzyme with endo activity, both showing activity of 40,000 LV g^{-1} and (C) another an alkaline triacylglycerol lipase enzyme with 50,000 TBU g^{-1} activity. The process demonstrates efficiency, versatility with up to 85% protein recovery from greaves and significantly reduced water and chemical consumption. The resulting hydrolyzed collagen, suitable as a retaining agent and biostimulant, was successfully used in retaining wet blue leathers. Still, as it did not contain chromium, this collagen is helpful for animal feed formulations [70].

Another study explored using tannery fleshings as an alternative to fishmeal in aquaculture. Fermented fleshings replaced varying percentages of fishmeal in the rohu fish (*Labeo rohita*) diet. The most successful results were observed when fishmeal was replaced by 75% fermented tannery fleshing flour, showing superior growth and nutritional indices in the fish. One of the studies listed in Table 3 concluded that recycling bovine tannery fleshings mitigates environmental issues associated with its disposal and offers a potential solution to reduce production costs in aquafeed processing [71]. Even after these promising results, potential toxicity remains a concern.

Addressing this, D'Agaro embarked on an 88-day seabass (*Dicentrarchus labrax)* growth experiment, encompassing eight isoproteic and isolipidic distinct diets. The diets included a C1 control diet based on fishmeal; diets containing tannery wastes S1 and S2 with 100 and 200 g kg^{-1}, respectively; AV1 and AV2 based on poultry meal; M1 and M2 with alfalfa concentrate; and A1 containing *Haematococcus fluvialis* meal. Results indicated that diets S2 and AV2, which partially replaced fishmeal with alternative protein sources by up to 40%, significantly reduced fish growth rates and exhibited poor fish conversion ratio values. Furthermore, introducing fleshing wastes to the seabass diet appeared promising but not economically viable [72]. There was no evidence of toxicity or contamination of fishes with diets S1 and S2 containing tannery wastes, which gives hope in using these residues, but more experiments are still necessary to discard future issues.

Table 3. Overview of research on utilizing nontanned fleshing wastes from tannery in animal feed formulations.

Authors Date	Type of Study	Main Findings	Results in Animals	Cite
Thazeem, B.; Preethi, K.; Umesh, M.; Radhakrishnan, S. 2018	The study type is experimental research where wet limed fleshings from bovine hides were treated and fermented, followed by the formulation of isonitrogenous diets for *Labeo rohita*, with varying replacement levels of fishmeal by fermented tannery fleshing flour. The ideal diet was then analyzed for multi-mycotoxins.	The study found that the fermented tannery fleshing flour (FTF) contained ten essential and six nonessential amino acids. Fish fed with a diet that replaced fishmeal with 75% FTF (diet FTF3) showed the best growth performance, nutritional metrics, and body composition. Additionally, a multi-mycotoxin analysis of FTF3 confirmed the absence of harmful feed toxins in the diet.	FTF3 diet helped to increase the size of fish from 1.57 to 9.54 cm and achieve an increment of 2.50 to 17.34 g kg^{-1} in body weight. The study did not investigate the flavor, toxicity, and other variables of interest for the commercialization of FTF3. The study suggested that diets based on tannery wastes can be a cost-effective, efficient, and safe protein alternative for aquatic animals.	[71]
D'agaro, E. 2003	The experimental research study, specifically a controlled growth trial of *seabass* fed varied diets, S1 and S2, including tannery fleshings, to evaluate their impact on growth. Diets containing tannery wastes S1 and S2 with 100 and 200 g kg^{-1}, respectively.	The primary finding of the study is that up to 40% of fishmeal (FM) in sea bass diets can be substituted with alfalfa concentrate without negatively impacting fish performance but not with tannery by-products.	Fish fed with diets S2 and AV2, which replaced 40% of fishmeal with alternative protein sources, displayed the lowest specific growth rate, leading to poorer feed conversion ratio values. Despite these variations, the overall body composition of sea bass remained largely consistent by the experiment's end.	[72]
Alam, M.J.; Amin, M.R.; Samad, M.A.; Islam, M.A.; Wadud, M.A. 2002	The type of study described is an experimental research study, specifically a controlled feeding trial. Diet 1 (10% protein concentrate), Diet 2 (5% PC + 5% tannery wastes), and Diet 3 (10% TW) for 144 days old Starbro broiler chicks.	The study indicates that tannery waste can be a cost-effective alternative in broiler diets. While feed consumption, live weight, feed conversion ratio, and survivability remained consistent across diets, there were significant differences in production cost and profitability.	Live weight, dressing percentage, neck, breast, thigh, drumstick, heart, liver, head and blood weights were almost similar between diets, but the profitability of Diet 1, Diet 2, and Diet 3 was 0.27, 0.90, and 1.27 USD kg^{-1}, respectively.	[73]
Rai, A.K.; General, T.; Bhaskar, N.; Suresh, P. V.; Sakhare, P.Z.; Halami, P.M.; Gowda, L.R.; Mahendrakar, N.S. 2010	The type of investigation described is an experimental research study specifically focused on optimization using response surface methodology (RSM) to enhance the fermentation process of tannery fleshings with a specific lactic acid bacterium (E. faecium HAB01).	The ideal conditions determined were an inoculum of 12.5% (v/w), glucose at 17.5% (w/w), and a fermentation duration of 96 h at a temperature of 37 ± 1 °C to achieve the highest degree of hydrolysis of 92%.	This study was not applied to feed animals but showed a good source of protein for animal food with better antioxidant properties than commercial animal diets.	[74]

Allam et al. directly transformed fleshings into flour destined as a dietary supplement for broiler chicks. First, the fleshings were boiled at 100 °C for 4–5 h, then dried and ground. When comparing the three diets, Diet 1 containing 10% protein concentrate, Diet 2 consisting of 5% protein concentrate and 5% tannery wastes, and Diet 3 incorporating 10% tannery waste, the findings show that the basic parameters such as feed intake, live weight, and feed conversion efficiency remain largely unaffected among the groups. Nevertheless, there is a notable variance in the cost of production and profitability, with diets incorporating tannery waste demonstrating enhanced profitability. Specifically, Diet 3 yielded a profitability of USD 0.13 per kilogram of live weight. While most meat yield traits were unaffected by the different diets, some specific characteristics such as gizzard and shank weight improved with increased tannery waste. The study concluded that producers can integrate residual fleshing from tanneries into broiler diets without causing adverse impacts [73].

A fermentation technique for delimed tannery fleshings was established to maximize protein hydrolysis and antioxidant activity using Enterococcus faecium HAB01 (GenBank #FJ418568). Under optimized conditions, which consisted of 12.5% (*v*/*w*) inoculum, 17.5% (*w*/*w*) glucose, and a fermentation period of 96 h at a temperature of 37 °C, maximal hydrolysis was achieved. The chemical evaluation of the hydrolysate unveiled an abundance of essential amino acids, particularly arginine and leucine when compared to a reference protein. Furthermore, the liquid portion of the hydrolysate exhibited robust antioxidant activities, suggesting its promising role as a high-quality feed ingredient [74]. These methods prove that it is possible to convert fleshing with no chromium content-rich protein sources for animal feed if considering quality and extraction processes.

3.2.2. Products Derived from the Residual Tallow in the Tanning Process

Due to its large volume, tallow has become a significant waste issue for slaughterhouses and tanneries. Most of it ends in landfills, with only a tiny fraction being recycled [75]. Freshly sourced beef tallow, coming directly from the animal's stomach after slaughter, holds superior quality [76–78]. In 2019, global tallow production reached 6,606,876,775 kg [79], positioning it as an economical source of edible fats. Tallow is abundant in polyunsaturated fatty acids, including linoleic and α-linolenic acids, with a higher triacylglycerol concentration in adipose tissue and a significant presence of phospholipids in muscle tissue [80]. Historically, this beef fat was a staple in candle making, lubricants, and even in the industrial preparation of French fries [81]. However, health concerns related to its high saturated fat content have diminished its dietary role, leading to its substitution for unsaturated vegetable oils [81]. Today, tallow is an additive in balanced animal feed [82,83].

Tannery tallow undergoes recycling via solvent extraction [84] and thermal processes, where it is cooked until it separates into fat, flesh, and water [85] despite the thermal methods' inefficiencies and high energy consumption. One study introduced a more efficient way of using solid-state fermentation. The researchers produced an enzyme (lipase) that effectively breaks down and solubilizes the fats, with 92% recovery when applied to tannery fleshing. This method offers a potential source for biodiesel production and repurposes the remaining residue as a protein-rich feed for animals [86]. A key challenge in fat recovery is achieving a high yield. Devaraj et al. designed an industrially viable process, employing 4% H_2SO_4 at 120 °C for 1.5 h, successfully extracting 98% of fat from leather fleshing waste. Subsequent analyses indicated that this fat has more potential utility as a biodiesel feedstock [87]. The extraction processes produce low-quality fats; thus, further investigation is required to refine these fats for consumption.

Cunha et al. [88] identified the optimal fat extraction conditions at 155 °C and 550,000 Pa. Under these conditions, 100% of the fat could be collected through simple decantation due to the insolubility between the lipophilic fat phase and the hydrophilic protein-rich phase. Nevertheless, these conditions yielded fat with a low iodine value, approximately 5 kg I_2/kg fat, and a high acid number, 5 mg KOH/g, for limed fleshings. The saponification values are also low, likely due to the impurity of the extracted fat. In the case of limed fleshings, $Ca(OH)_2$ acts similar to a cement, reducing the effectiveness of thermal treatment or solvent extraction. Therefore, the process of fat extraction from fleshing presents several challenges that need to be addressed to improve efficiency and product quality.

In addition to the previously described defatting methods, another innovative process has been explored. Instead of using traditional solvents, this method exclusively uses supercritical CO_2 in specialized high-pressure view cell equipment to extract fat from double-face lambskins. By optimizing conditions to 2×10^7 Pa, 80 °C temperature, and a duration of 2 h, the researchers achieved a fat yield of 78.57%. The results suggest that supercritical fluid CO_2 extraction is a highly efficient and environmentally friendly alternative to fat separation processes [89].

While there is a lack of research on using recycled tallow in animal feed formulas, tallow has been successfully incorporated into feeds for cattle, equines [90], lambs, poultry [91], and other animal species due to its palatability and nutrient content. Okur, N. investigated the effects of soy oil, poultry fat, and tallow in broiler feed at fixed energy: protein ratio on field and slaughter parameters; see Table 4. The research evaluated several parameters; see Table 4. The study was conducted over 41 days with 12,600 Ross 308 broiler chicks. Ten different diets were used, including soy oil in the starter poultry fat, tallow in the grower, and various combinations in the finisher. The results indicated that using tallow instead of Soy oil, especially in grower feed, improved field performance. The study concluded that animal fat instead of soy oil could be an economical alternative if specific ratios are maintained [91].

Research performed by Wickramasuriya et al. involved 384 one-day-old Ross 308 broiler chicks, which were subjected to eight different dietary treatments. These diets were primarily corn–soybean meal-based, with beef tallow as the fat source. The study found that broiler chickens fed a diet supplemented with Polysorbate-20 and Candida rugosa lipases (NC + POL + CRL) exhibited improved growth performance, especially during the grower phase from day 21 to 35. These chickens also showed enhanced gut health, with increased villi height and a higher villi-to-crypt ratio. Furthermore, the NC + POL + CRL diet improved fat and energy digestibility compared to the negative control diet. The study concluded that combining Polysorbate-20 with Candida rugosa lipases can enhance the growth performance of broiler chickens on a low-energy diet without affecting other health parameters [92].

In a study by Ahmed et al., a 63-day experiment with 15 lambs evaluated three dietary treatments: T0 (control without beef tallow), T1 (2% beef tallow), and T2 (4% beef tallow) with five lambs per group; see Table 4. Notably, the T1 group exhibited a marked rise in body weight and improved feed conversion ratio. Meat quality and chemical composition remained consistent across all groups. However, lambs in the T1 group saw an 11.5% surge in cholesterol levels. The findings suggest that introducing 2% beef tallow into lamb diets can boost their performance without any detrimental impacts [93].

Lopez et al. highlighted weight gain in younger lambs, contrasting with Ahmed et al.'s broader approach. Yet, both studies underscored the advantages of adding tallow to the diet [94]. Considering its use in cattle feed requires careful dosing due to bovine spongiform encephalopathy (mad cow disease) risk. In the United States, the FDA's 2018 decree [95] regulates the use of tallow in animal feed, prohibiting the use of tallow with more than 0.15% insoluble impurities for ruminant meal.

The evidence indicates that incorporating tallow into animal feed is practical and cost-effective. Furthermore, tallow can be sustainably sourced from tannery waste through appropriate recycling, recovery, and purification processes.

Table 4. Overview of research on utilizing tallow in animal feed formulations.

Authors Date	Type of Study	Main Findings	Results in Animals	Cite
Okur, N. 2020	This investigation focuses on the effects of using soy oil (SO), poultry fat (PF), and tallow (T) in broiler feed at a fixed energy: protein ratio on field and slaughter parameters. The research evaluated parameters such as average live weight (ALW), feed conversion ratio (FCR), production efficiency factor (PEF), carcass weight (CW), carcass yield (CY), heart–liver weight (HLW), heart–liver yield (HLY), abdominal fat weight (AFW) and abdominal fat yield (AFY)	The results indicated that animal fat (PF and T) instead of SO, especially in grower feed, improved field performance parameters except for mortality. However, this improvement was not observed in slaughter performance parameters except for CW, HLW, and HLY. The research determined that substituting SO with animal fat could be cost-effective when adhering to specific proportions.	Tallow in feeds at fixed energy protein ratio, during field performance ALW 2.401 FCR 1.828 PEF 301.54 Mortality 5.88 Tallow in feeds at fixed energy: protein ratio slaughter performance CW 1682 CY 67.40 AFW 39 AFY 2.35 HLW 60 HLY 3.57	[91]
Wickramasuriya, S.S.; Macelline, S.P.; Cho, H.M.; Hong, J.S.; Park, S.H.; Heo, J.M. 2020	The study aimed to explore the impacts of dietary emulsifiers and lipase supplementation on various parameters in broiler chickens, such as growth performance, blood metabolites, intestinal organ weight, gut morphology, nutrient digestibility, carcass measurements, and meat quality. All diets included the same quantity of tallow.	The study concluded that combining Polysorbate-20 with Candida rugosa lipases can enhance the growth performance of broiler chickens on a low-energy diet without affecting other health parameters.	Effect of diet NC + POL + CRL on meat quality of broiler chickens NC + POL + CRL, lightness 55.21, redness 5.12, yellowness 15.41, cooking loss 24.17, WHC 79.72%, and pH 6.02 Effect of NC + POL + CRL diet on carcass measurements Leg 26.27%, breast 9.10%, abdominal fat 0.9%	[92]
Ahmed, S.; Khatun, J.; Manirul, M.; Kabirul, M.; Niaz, S.M.; Abdullah Al Noman, M.; Zohorul M. 2015	In this experimental study, three–four-month-old male lambs, averaging 10 kg, were acclimatized for 15 days and divided into three groups: T0 (no tallow), T1 (2% tallow), and T2 (4% tallow) each with five lambs. Diets replaced corn and soy with tallow, maintaining consistent crude protein.	Supplementing lamb diets with 2% beef tallow (T1 group) resulted in the highest total weight gain and proved the most cost-effective. However, the highest dressing percentage was observed in the T2 group. The beef tallow treatments did not significantly impact the proportion of various organs.	The highest total weight gain, 4.68 kg, was observed in the T1 group, showing higher growth and superior FCR than the control group T0. The T1 group showed the most cost-effective results, suggesting higher profits when sheep rations are supplemented with 2% beef tallow. The highest dressing percentage was found in the T2 group, 44.05%.	[93]

Table 4. *Cont.*

Authors Date	Type of Study	Main Findings	Results in Animals	Cite
López-Aguirre, S.; Pinos-Rodríguez, J.M.; Vicente, J.G.; Rangel, H.L.; de la Cruz, A.; Domínguez-Vara, I.A. 2020	The work analyzes beef tallow dietary variations on lamb growth, rumen activity, and meat/carcass attributes. Subjects: 21 five-month-old male Rambouillet lambs. Diet: 0, 20, 40 g beef tallow/kg DM with consistent energy/protein. Duration: 60 days (15 for adaptation, 45 for evaluation). Metrics: weight, intake, rumen analysis, carcass weight, meat quality.	It is possible to conclude that increasing tallow in the diet: Increases saturated fatty acid contents, daily metabolizable energy intake, carcass dressing, fatness, and intramuscular fat content. The diets keep similar growth metrics and ruminal fermentation characteristics. Carcass attributes, such as classification, weight, muscle conformation, longissimus muscle area, and individual fatty acids in meat, remained unaffected. Tallow addition did not influence meat characteristics post mortem.	Diet 40 g kg^{-1} amount of tallow. Growth performance Final gain 15.80 kg Ruminal fermentation pH 5.9, acetate 47.6 mol mol^{-1} Propionate 35 mol mol^{-1} Butyrate 17.4 mol mol^{-1} Carcass characteristics Weight 23 kg Dressing 51.9% Length 67.9% Leg length 43.8 cm Fatness degree 4.2	[95]

3.2.3. Recycling of Wet Blue Waste and Its Potential Alternatives for Animal Nutrition

After undergoing the chromium tanning process, the leather is termed wet blue. The skin's thickness is harmonized during the subsequent finishing stages, producing wastes such as shavings and wet blue sanding dust [96]. These wet blue residues, which contain various levels of chromium-stabilized collagen, have seen research advancements that enable the reduction in chromium content. After chrome removal, theoretically, collagen-based protein is appropriate for feeding poultry, ruminants [97], and pets. It is vital to exclude chromium from the final product due to its notorious toxicity and associated health risks, from allergic reactions to cancer [98].

One noteworthy advancement is the increase in studies for efficient chrome extraction from protein hydrolysates [99,100]. This process leverages collagen of different qualities, which can be converted into valuable products such as gelatin, elastin, and animal feed. The efficiency and Cr (III) recovery depends on extraction methods; see Table 5. Furthermore, the profitability of this process depends on the market demand for these protein-based products. Recycling wet blue waste plays a dual role; it not only aids in reducing waste within the leather industry but also generates substantial economic value, as in the case of Bangladesh, which, in 2022, started exporting wet blue waste, capitalizing on its growing demand and utility worldwide [101].

Table 5. Recovery of chromium from different processes.

Recovery Method	Initial		Results		Cite
Microbial fermentation with *Aspergillus carbonarius*	82.00 -	$g\ kg^{-1}$ protein $g\ kg^{-1}$ chrome	* 68.40 * 28.00	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[102]
Hydrolysis with MgO and trypsin enzyme	908.10 34.20	$g\ kg^{-1}$ protein $g\ kg^{-1}$ chrome	646.30 1.47	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[103]
Enzymatic hydrolysis with *alcalase*	- -	$g\ kg^{-1}$ protein $g\ kg^{-1}$ chrome	867.70 3.93	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[104]
Alkaline protease	708.00 40.50	$g\ kg^{-1}$ protein $g\ kg^{-1}$ chrome	- -	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[105]
Pressure assisted hydrolysis with NaOH in an autoclave	20.50 24.8	$g\ kg^{-1}$ protein (N) $g\ kg^{-1}$ chrome	- 496.00	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[106]
Sodium and calcium hydroxide hydrolysis	804.40 -	$g\ kg^{-1}$ protein (N) $g\ kg^{-1}$ chrome oxide	570.00 0.0054	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[107]
Alkaline hydrolysis in steam explosion system with CaO	146.00 45.60	$g\ kg^{-1}$ protein (N) $g\ kg^{-1}$ chrome oxide	** 44.00 ** 5.5	$g\ kg^{-1}$ protein $mg\ kg^{-1}\ Cr^{3+}$	[108]
Ultrasound assisted with ethylenediaminetetraacetic acid	25.28	$g\ kg^{-1}$ chrome	505.00	$mg\ kg^{-1}\ Cr^{3+}$	[109]

* Original data: protein 68.4 g/L, Cr^{3+} 0.028 g/L; ** to compare the equivalence, 1 L = 1 kg was used.

The environmental challenge posed by chromium-tanned leather waste disposal stems from the potential conversion of trivalent chromium salts to the more soluble and carcinogenic chromium (VI) salts. This conversion can be instigated by factors such as UV light exposure, temperature fluctuations above 353 K, changes in humidity, natural pH shifts in landfills, and the leather hydrolysis process.

- In an alkaline medium:

$$2Cr_2O_3 + 8OH^- + 3O_2 \rightarrow 4CrO_4^- + 4H_2O\ \Delta G^0 < 0 \tag{1}$$

- In an acid medium:

$$2Cr_2O_3 + 2H_2O + 3O_2 \rightarrow 4Cr_2O_7^{2-} + 4H^+\ \Delta G^0 < 0 \tag{2}$$

These reactions (1) and (2) are pH sensitive and can be accelerated in metal soils such as those containing cerium and manganese [110,111]. To avert Cr (VI) contamination and ensure premium collagen quality, collagen extraction from chromed wastes involves acid, basic, enzymatic hydrolysis [112], and combined methods [113,114]. These extraction processes require controlling pH and keeping temperatures between 70 °C and boiling. These unique measurements during hydrolysis, as supposed, increase the production costs. In these processes, protein yields vary from 25 to 30%; likewise, high-quality gelatins have been obtained that can compete in price with commercial gelatins [115].

A notable collagen purification method by Chaudhary and Pati [116] involved protease, α-amylase, and lime to treat a 3:1 water–collagen mix at different times and temperatures with a maximum recovery of 12%. Birds fed with diets replacing soybean meals with 20% and 30% protein hydrolysate exhibited more significant weight gain than those on a standard diet. Heavy metal tests further confirmed that the meat's chromium levels remained within 67.83 and 82.12 ppb, under safe limits.

Another method extracted collagen from dried wet blue remnants using 0.5 M acetic acid and 5 mM EDTA in a 1:10 weight/volume ratio for 24 h. The extracts were filtered and salted with NaCl to a final concentration of 0.9 M. The precipitate was dissolved in 0.5 M acetic acid, reprecipitated with 0.9 M NaCl, then dissolved in a minimal volume of 0.1 M acetic acid and lyophilized. This process yielded acetic acid-soluble collagen at a rate of 6.15%. A SDS-PAGE analysis confirmed the collagen purity and identified it as type I, making this optimal for animal consumption [117].

3.3. Evaluation of Security of Recycled Solid Chromed Tannery Wastes for Animal Feed

Trace amounts of Cr (III) are integral to human metabolic functions. While the upper intake level for chromium has not been defined due to the absence of observed toxicities from food and prolonged high-dose supplement intake, recommended doses do vary. The recommendation for women aged 19–50 is 25 micrograms daily, increasing to 45 micrograms during lactation [118]. Meanwhile, the FDA advises an intake of 120 micrograms daily [119], whereas the no observed adverse effect level is 1468 mg kg^{-1}-day^{-1} recommended by EPA [120]. Nonetheless, an excessive presence of heavy metals can lead to severe adverse impacts on human health [121]. Assuming that Cr (III) is the only contaminant, a 65 kg individual could safely consume up to 285 g of poultry daily. However, the potential conversion of Cr (III) to the more dangerous Cr (VI) during cooking raises genuine concerns about meat chemistry [122].

Hexavalent chromium, or Cr (VI), is particularly hazardous; prolonged exposition to this ion can lead to significant health issues such as skin disorders, respiratory problems, gastrointestinal tract damage, provoking cancer, and severe DNA damage depending on the exposure route [123]. The Office of Environmental Health Hazard has set the maximum allowable dose level for Cr (VI) at 8.2 μg day^{-1} [124]. However, findings by Mazumder et al. [125] sounded alarm bells. Chickens fed on tannery waste-derived protein showed Cr (VI) levels between 86 and 177 μg kg^{-1} in over 25% of samples, potentially exceeding the safety threshold [125]. Such findings cast serious doubt on using chromed waste residues in animal feeds.

Interestingly, if present in feed at concentrations below 0.6 mg mL^{-1} (maximum 0.46 μg Cr mL^{-1}), chrome hydrolysates have no adverse effects on zebrafish embryo development. This safety with zebrafish embryos is consistent across various extraction methods such as alkaline, enzymatic, or combined, even when extracted collagen contains 783 mg kg^{-1} of chromium [126].

In Bangladesh, chrome-containing constituents such as raw skin trimmings and wet blue scraps are used in poultry feed due to their high protein content. However, there is a rising concern over chromium contamination in poultry, posing potential risks to human consumers. A study by Ahmed et al. revealed that while specific poultry feed components maintained chromium within safe limits, others showcased alarmingly high concentrations. The experiments with broiler chickens (*Gallus gallus domesticus*) fed on chrome-infused feed revealed that raw skin trimmings and several poultry feed samples contained chromium levels below 0.03 mg kg^{-1}. In contrast, wet blue shaving dust, starter feed (FS10), and grower feed (FS11) exhibited significantly elevated chromium concentrations, ranging from 3.02 to a staggering 29,854.4 mg kg^{-1} [127].

Moreover, processes applied to these tannery wastes did not reduce chromium concentration to safe levels. In the case of chickens consuming these feeds, chromium accumulation ranged between 0.42 and 0.84 mg kg^{-1} across various body parts. Such levels surpass the daily adequate intake for humans. Crucially, for broiler chicken feed, regulations stipulate that total chromium from supplemental sources should not exceed 0.2 mg kg^{-1} [128]. This study underlined the need for stricter control measures in feed formulations to safeguard human health. This concern was echoed in the research by Bari et al. [129], where broiler chicken, desi chicken, and free-ranging chicken were fed chromium shavings, with chromium concentrations varying from 0.27 to 0.98 mg/kg and lead concentrations ranging from 10.27 to 10.36 mg kg^{-1}. Given that these chromium concentrations exceeded the recommended dose of 0.2 mg kg^{-1}, the findings highlighted potential risks for humans consuming poultry fed with chromed tannery waste-based concentrates.

Silva et al. investigation further highlighted the risks of using wet blue in animal feeds. Upon feeding 48 Wistar diets containing 0 to 50% of tannery chromed wastes, adverse effects on the animals' weight gain and kidney impacts were observed. The damage was directly proportional to the concentration of wet blue. The injuries were even worse with diets that replaced 25% to 50% of the weight with previously purified wastes (80% less chrome). The authors recommend removing at least 99% of chrome to consider wet blue for animal feed [130].

However, not all tannery waste derivatives pose risks. A study on delimed tannery fleshing hydrolysates, processed through acid hydrolysis and fermentation, showed promise. The investigation used male Wistar rats fed diets up to 15% of these hydrolysates. The study comprised acute toxicity assessments over 15 days and subacute evaluations spanning 30 days. The biochemical examinations of all serum, liver, and urine samples showed no notable alterations. This consistency was also evident in the liver histology outcomes, comparable to those from the control group. Thus, the study conclusively determined that incorporating up to 15% of delimed tannery fleshing hydrolysates into diets is safe, making them a valuable protein-rich ingredient for livestock feed formulations [131].

Lastly, a study assessing tannery waste protein concentrate as a potential replacement for a commercial protein named Jasoprot in cattle feed revealed optimistic results. Twelve cattle were subjected to various diets. The results indicated that diets with tannery waste protein concentrate significantly improved weight gain and profitability. Notably, the concentrate was free of aflatoxin and met typical beef chemical standards, including safe chromium levels under 24 ng g^{-1} (2 μg/serving). Organoleptic scores remained consistent across diets, suggesting no compromise in meat quality. Thus, combined with Jasoprot, tannery waste protein concentrate emerged as a cost-effective substitute in the cattle industry without affecting meat or carcass quality [132,133].

In Figure 4, a unanimous agreement among the surveyed authors indicates the benefits of tallow in animal diets. D'Agaro, E. remains the outlier for untanned wastes, not finding compelling evidence to use collagen from these residues in animal feed [72]. The predominant concern with chromed tannery wastes lies in the high chromium levels in extracted collagen, potentially endangering humans eating such meat. While studies by Silva et al. [130], Jini et al. [131], Jahangir-Alam et al. [133], and Zhao et al. [126] saw no issues with tannery wastes, five other researchers identified chromed wastes as dietary risks for animals. This emphasizes the need for effective dechroming before using tannery residues in animal feeds.

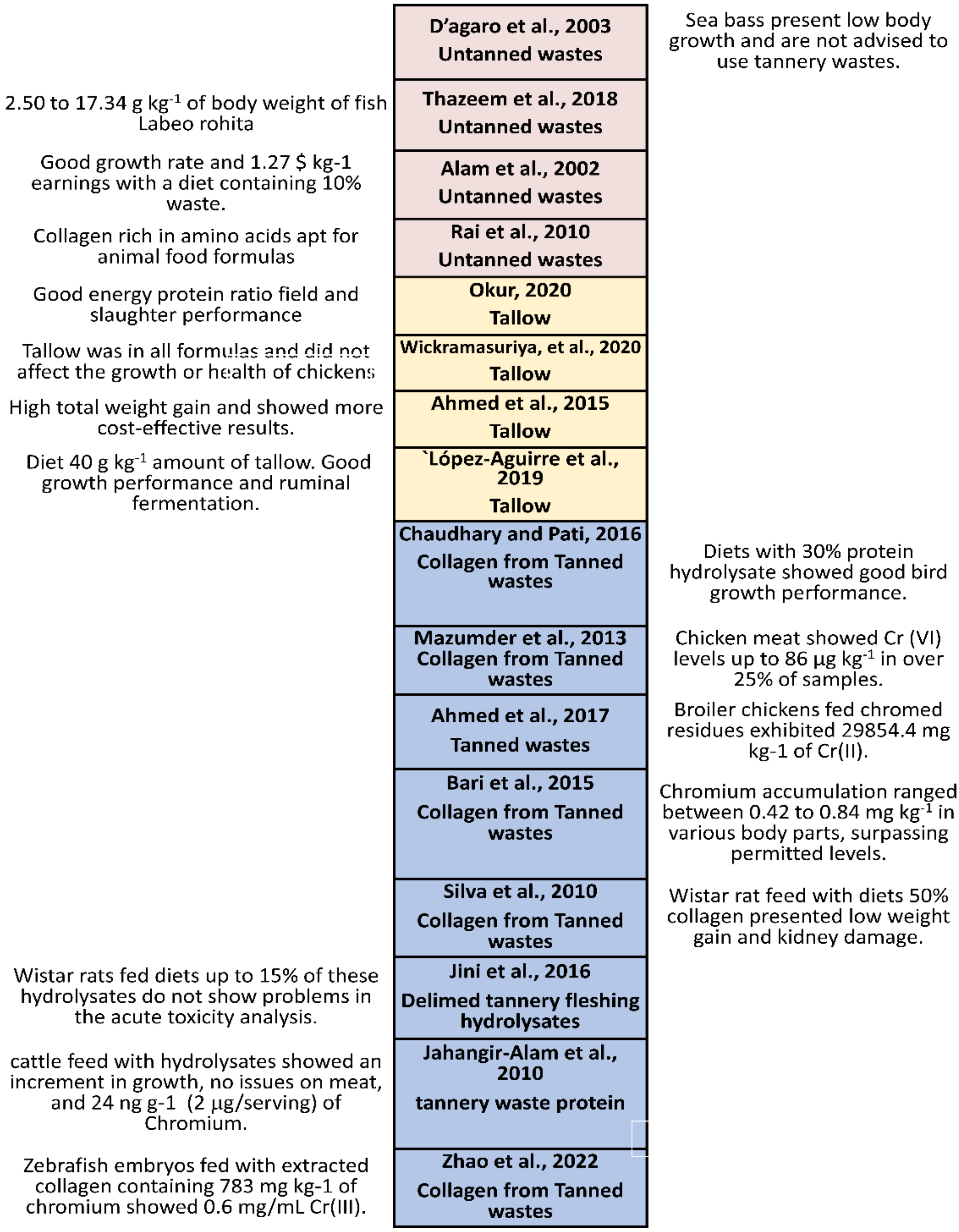

Figure 4. Comparative analysis of researchers' views on recycling untanned and tanned wastes and tallow. The central section lists authors; the right side indicates nonrecommended uses, and the left side shows positive usage recommendations [71–74,91–95,116,125–133].

3.4. Analysis of Global Leather Waste Trade Data

According to the United Nations Comtrade database and Observatory of Economic Complexity (OEC) [134,135], the trade of leather waste, leather dust, and raw animal hides saw steady growth in their business between 2020 and 2021. In global trade, leather waste occupied the 1200th position as the most traded product, with a cumulative trade value of USD 37,500,000 in 2021.

China is the top exporter, primarily due to its manufacturing prowess, with Indonesia as the leading importer, as shown in Figure 5. This highlights the significance of leather waste trade, potential growth, or partnerships based on trade dynamics. While the exact volumes of tannery wastes used for animal feed are unclear, their global economic impact is evident. Bangladesh uses tanning residues for poultry feed for economic reasons, but its safety needs further study. A wealth of waste exists for animal feed, with ample suppliers available [135].

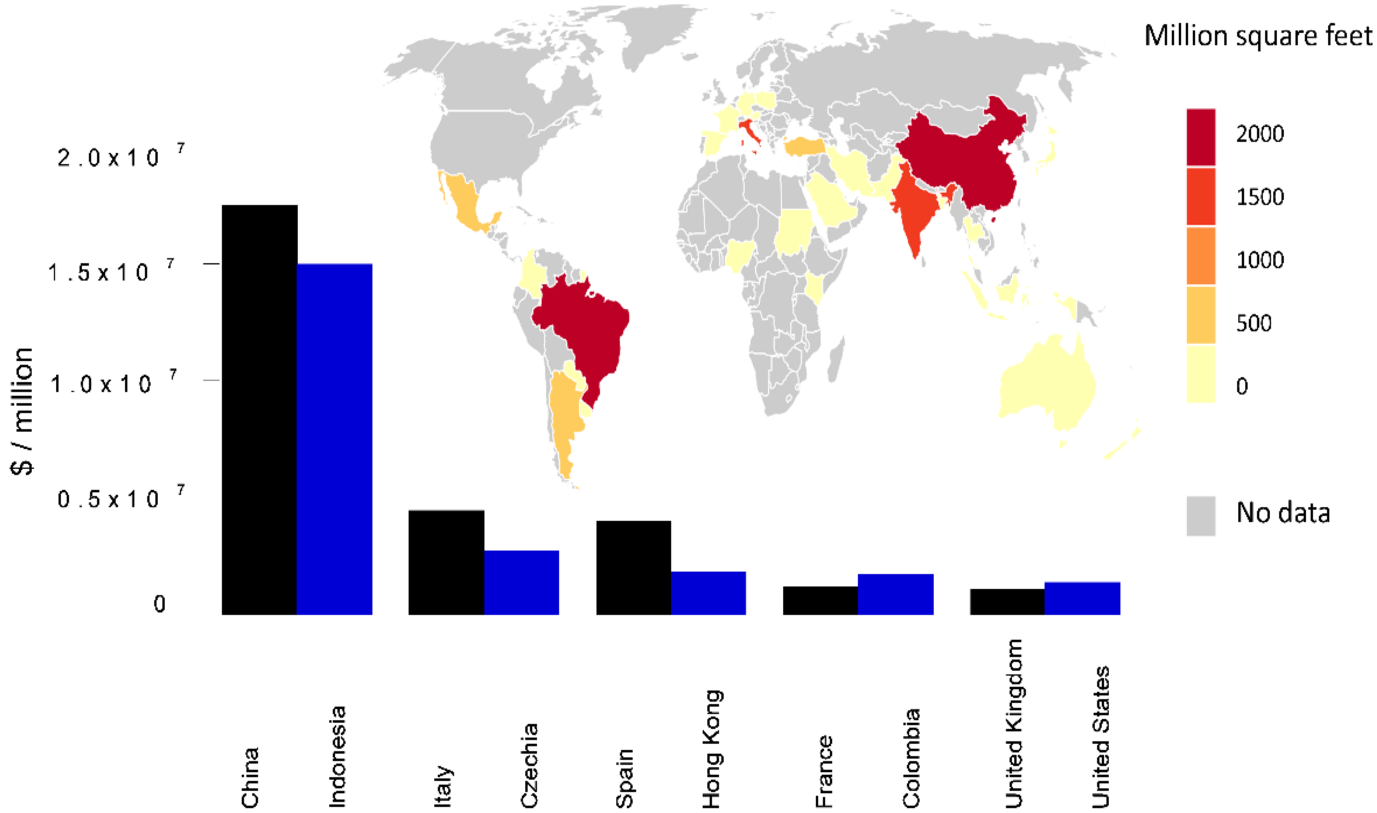

Figure 5. Contemporary trade insights of leather waste—leading exporters (■) and prominent importers (■) in 2021 [134]; the embedded map shows the manufacture of leather around the world in 2015 in million square feet [135].

3.5. Economic Implications of Dechroming Tannery Waste Residues

Collagen extraction and chrome recovery from tannery residues are understudied, with most data from older research or being proprietary; see Table 6. Environmental regulations prioritize chromium recovery from wastewater. Untanned collagen-rich residues, typically sent to gelatin manufacturers, are easier to recycle than tanned residues. The latter requires intensive processing compared to simple hydrolysis. Pretreatments help to reduce chromed residue purification costs [136], and after solubilizing the solid wastes, the recovery of chromium can be performed in dechroming plants. Low et al. developed a technology where an imprinted polymer bead can recover chromium from tanning liquor, improving the sustainability and efficiency of the tanning industry by reducing contamination in waterways. The economic analysis, based on an industrial-scale chromium recovery plant designed to process 5000 L of tanning liquor per hour, shows incomes, and the author recommends this plant for medium- or high-throughput enterprises. An alternative solution [137], especially in regions with multiple small tanneries, is establishing a centralized chromium recovery plant.

Table 6. Cost of plants to dechrome tannery wastewater.

Costs Related to the Plant	Operating Conditions	Payback Period	Country / Year	Cite
Plant construction: USD 357,833 Maintenance costs: 4% of capital cost Chromium value: USD 1.1 kg^{-1} Hazardous disposal savings: USD 74.5 TON^{-1}	600 kg day^{-1}	2.56 years	New Zealand	[136]
Capital cost: USD 5 million Chrome content in the spent liquor: 3–4 g L^{-1} as Cr_2O_3 Regenerated chrome liquor: USD 0.20 kg^{-1} Cr_2O_3 content: 9–10% by weight. Effluent treatment: USD 2.6 m^{-3} Sludge production: 1600 TONS Cost of landfilling: USD 66.8 TON^{-1}	400–500 m^3 day^{-1} of spent chrome liquor in an 8 h shift	10 years	Bangladesh 1981 2000	[137]
Initial fixed investment: USD 4083 Operating cost: USD 17,978 Benefit-to-cost (B/C) ratio: 4.67, Net present value (NPV): +USD 80,864	No data	100 to 241 days	Pakistan 1994 2004	[138]
Pre-production expenditure: USD 10.199 Total initial fixed investment: USD 97.136 Pollution charges: USD 115.613 Total benefits in 2000–2001: USD 27.355 Benefit-to-cost (B/C) ratio: 0.5 Net present value: −USD 176.431 Total annual operating cost: USD 176.43	No data	36 years	Pakistan 2007	[139]

Buljan [138] stated that a central chrome recovery unit in Santa Croce sull'Arno, Italy, was established, recovering 490 tons of Cr (III) 2000 for USD 1.45 million. While India had about 100 chrome recovery units using magnesium oxide, many ceased operations due to leather quality and cost concerns, similar to China.

Khan et al. deemed the chromium recycling plant at Riaz Tanneries economically and environmentally beneficial. Despite its environmental importance, another study by Khan et al. found the plant's financial model unviable without adjustments, such as alternative machinery suppliers and better integration with tannery operations [139].

The feasibility of industrial-scale dechroming processes depends on the industry, chosen method, and factors such as regional differences, available technology, and research advancements, as illustrated in Table 6. Some processes may be more profitable in certain countries due to these variables.

4. Conclusions

Collagen, which makes up 21.5% of rawhide trimmings, can be extracted, achieving up to a 75% yield, resulting in products with notable antioxidant properties. Remarkably, replacing traditional fishmeal with 50% fermented tannery fleshing flour in *Labeo rohita* diets led to promising growth and nutritional outcomes. Additionally, using fleshing-derived flour in broiler chick diets showed no adverse effects and increased profitability by USD 0.13 per kilogram of live weight.

Tallow, extracted from untanned tannery wastes using advanced techniques such as hydrolysis and fermentation, can achieve up to a 98% yield. Feeds enriched with this tallow have demonstrated enhanced growth in broilers and lambs when compared to standard diets. The positive results in animal development suggest the potential of harnessing tallow from untanned tannery residues.

However, a significant concern arises from chromium solid waste. Most experts believe these wastes need rigorous purification to remove residual chromium before being used in animal feed formulations. The challenge lies in the absence of a foolproof process to purify the extracted collagen and concerns about potential human contamination. Therefore, more research is essential before endorsing such residues for animal nutrition.

Untanned tannery residues present more opportunities than tanned ones to serve as animal feed sources. While the potential of tannery-derived tallow is evident, more in-depth exploration is required, especially concerning the purification of chromed residues for animal feed.

5. Future Research Prospects

The utilization of tannery waste in animal feed presents both opportunities and challenges. Critical areas for future research include a more profound economic analysis of this practice, an understanding of its impact on animal productivity, and a thorough cost–benefit assessment. Additionally, the development of cost-effective chromium purification methods and studies on potential chromium conversion during food preparation are essential to ensure the safety and viability of this approach. Addressing these research gaps is crucial for the sustainable and safe adoption of tannery waste in animal feed.

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