Tannery Solid Wastes for Animal Feed

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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.

leather waste animal feed wet blue recycling global trade

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][4][5][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][29][30], elastin [31], among others [32].

2. Solid Waste Tannery Residues

The leather production process generates a diverse array of wastes, each with its unique characteristics and potential environmental ramifications. 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.

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

3.1. 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 [44]. The surplus skin and the portions not utilized in the tannery are sold to manufacturing units to produce gelatin/collagen [45] and adhesives [46]. 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 [47], hydrogen generation [48], and soap manufacturing [49]. Furthermore, they undergo processing to yield meals enriched with protein and fat, suitable for animal feed [50], 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 [51][52]. Various methods, including acid, basic and enzymatic hydrolysis, can extract the proteins in the form of collagen [53]. 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 [54].

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 [55].

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.

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 [56].

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.

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 [57].

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 [58]. 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. 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 [59]. Freshly sourced beef tallow, coming directly from the animal’s stomach after slaughter, holds superior quality [60][61][62]. In 2019, global tallow production reached 6,606,876,775 kg [63], 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 [64]. Historically, this beef fat was a staple in candle making, lubricants, and even in the industrial preparation of French fries [65]. However, health concerns related to its high saturated fat content have diminished its dietary role, leading to its substitution for unsaturated vegetable oils [65]. Today, tallow is an additive in balanced animal feed [66][67].

Tannery tallow undergoes recycling via solvent extraction [68] and thermal processes, where it is cooked until it separates into fat, flesh, and water [69] 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 [70]. 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 [71]. The extraction processes produce low-quality fats; thus, further investigation is required to refine these fats for consumption.

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 [72].

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 [73], lambs, poultry [74], 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. The research evaluated several parameters. 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 [74].

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 [75].

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. 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 [76].

3.3. 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 [77]. 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 [78], 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 [79].

One noteworthy advancement is the increase in studies for efficient chrome extraction from protein hydrolysates [80][81]. 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. 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 [82].

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:

$$2Cr_2O_3+8OH^-+3O_2 \rightarrow 4CrO_4^-+4H_2O \quad \Delta G^0<0 \quad (1)$$

- In an acid medium:

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

These reactions (1) and (2) are pH sensitive and can be accelerated in metal soils such as those containing cerium and manganese [83][84]. To avert Cr (VI) contamination and ensure premium collagen quality, collagen extraction from chromed wastes involves acid, basic, enzymatic hydrolysis [85], and combined methods [86][87]. 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 [88].

4. 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 [89]. Meanwhile, the FDA advises an intake of 120 micrograms daily [90], whereas the no observed adverse effect level is 1468 mg kg^{-1}-day^{-1} recommended by EPA [91]. Nonetheless, an excessive presence of heavy metals can lead to severe adverse impacts on human health [92]. 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 [93].

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 [94]. The Office of Environmental Health Hazard has set the maximum allowable dose level for Cr (VI) at 8.2 μg day^{-1} [95]. However, findings by Mazumder et al. [96] 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 [96]. 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 [97].

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} [98].

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} [99]. This 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. [100], 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 [101].

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 [102].

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 [103][104].

5. Analysis of Global Leather Waste Trade Data

According to the United Nations Comtrade database and Observatory of Economic Complexity (OEC) [105][106], 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. 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 [106].

6. 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. 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 [107], 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 [108], especially in regions with multiple small tanneries, is establishing a centralized chromium recovery plant.

Buljan [109] 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 [110].

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