RECENT DEVELOPMENTS IN ENVIRONMENT-FRIENDLY METHODS FOR VALUING LEATHER WASTE AS A MEANS OF PROMOTING THE CIRCULAR ECONOMY: A COMPREHENSIVE REVIEW

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RECENT DEVELOPMENTS IN ENVIRONMENT-FRIENDLY METHODS FOR VALUING LEATHER WASTE AS A MEANS OF PROMOTING THE CIRCULAR ECONOMY: A COMPREHENSIVE REVIEW

ABSTRACT. The leather processing industry produces a significant quantity of waste materials, which can be treated in a manner that is consistent with the concepts underlying the circular economy. This article provides an overview of ways to recycle substances or energy from tannery waste, such as thermal, biological, chemical and other procedures. These approaches have the potential to facilitate the recovery and recycling of a diverse range of recyclable chemical substances like chromium, fats, gelatin vitamins, hydrolysate and minerals, biomass, and microbial waste products for use in other manufacturing operations. All the methods related to leather waste valorization have been discussed in this study to illustrate the recent development in techniques and processes of leather waste. The incorporation of the concept of circular economy has also been depicted. The premise of the circular economy model is that any waste product from the leather industry may be recycled and utilized again in the leather-producing process or in other related sectors. This study demonstrates that the circular economy approach to leather production offers chances for collaboration and innovation across several industries. Collaboration among organizations may lead to the discovery of innovative methods to minimize waste, enhance productivity, and extract value from resources that would otherwise be disposed of. The overview also addresses the state of waste legislation today and how it affects the environment. Technologies for sustainable and intelligent valuation allow for high recycling levels without negatively impacting the natural environment.
KEY WORDS: tannery, waste, valorization, sustainability, chromium

PROGRESE RECENTE PRIVIND METODELE ECOLOGICE DE VALORIZARE A DEȘEURILOR DE PIELE CA MIJLOC DE PROMOVARE A ECONOMIEI CIRCULARE: O REVIZUIRE CUPRINZĂTOARE

REZUMAT. Industria de prelucrare a pielii produce o cantitate semnificativă de deșeuri, care pot fi tratate în concordanță cu conceptele care stau la baza economiei circulare. Acest articol oferă o privire de ansamblu asupra modalităților de reciclare a energiei sau a substanțelor din deșeurile de tăbăcărie, prin procese termice, biologice, chimice și alte procese. Aceste abordări au potențialul de a facilita recuperarea și reciclarea unei game diverse de substanțe chimice reciclabile, cum ar fi cromul, grăsimile, vitaminele din gelatină, hidrolizatul și mineralele, biomasa și deșeurile microbiene pentru utilizare în alte operațiuni de producție. În acest studiu s-au discutat toate metodele legate de valorificarea deșeurilor pentru a ilustra progresele recente privind tehnicile și procesele de gestionare a deșeurilor de piele. De asemenea, a fost descrisă încorporarea conceptului de economie circulară. Premisa modelului economiei circulare este că orice produs rezidual din industria pielăriei poate fi reciclat și utilizat din nou în procesul de producție a pielii sau în alte sectoare conexe. Acest studiu demonstrează că abordarea producției de piele în termeni de economie circulară oferă șanse de colaborare și inovare în mai multe industrii. Colaborarea între organizații poate duce la descoperirea unor metode inovatoare pentru a reduce la minimum risipa, a spori productivitatea și a extrage valoare din resursele care altfel ar fi eliminate. Prezentarea generală abordează, de asemenea, starea legislației actuale privind deșeurile și modul în care acestea afectează mediul. Tehnologiile pentru valorizarea durabilă și inteligentă a deșeurilor permit niveluri ridicate de reciclare fără a avea un impact negativ asupra mediului natural.
CUVINTE CHEIE: tăbăcărie, deșeuri, valorificare, durabilitate, crom

DÉVELOPPEMENTS RÉCENTS DANS LES MÉTHODES RESPECTUEUSES DE L'ENVIRONNEMENT POUR LA VALORISATION DES DÉCHETS DE CUIR COMME MOYEN DE PROMOUVOIR L'ÉCONOMIE CIRCULAIRE : UN BILAN COMPLET

RÉSUMÉ. L'industrie de transformation du cuir produit une quantité importante de déchets qui peuvent être traités d'une manière cohérente avec les concepts qui sous-tendent l'économie circulaire. Cet article donne un aperçu des moyens de recycler les substances ou l'énergie des déchets des tanneries, telles que les procédures thermiques, biologiques, chimiques et autres. Ces approches ont le potentiel de faciliter la récupération et le recyclage d'une gamme diversifiée de substances chimiques recyclables comme le chrome, les graisses, les vitamines de la gélatine, les hydrolysats et les minéraux, la biomasse et les déchets microbiens pour une utilisation dans d'autres opérations de fabrication. Toutes les méthodes liées à la valorisation des déchets de cuir ont été abordées dans cette étude pour illustrer l'évolution récente des techniques et procédés de gestion des déchets de cuir. On a décrit également l'intégration du concept d'économie circulaire. Le principe du modèle d'économie circulaire est que tout déchet de l'industrie du cuir peut être recyclé et réutilisé dans le processus de production du cuir ou dans d'autres secteurs connexes. Cette étude démontre que l'approche de l'économie circulaire dans la production du cuir offre des opportunités de collaboration et d'innovation entre plusieurs secteurs. La collaboration entre les organisations peut conduire à la découverte de méthodes innovantes pour minimiser les déchets, améliorer la productivité et extraire de la valeur de ressources qui autrement seraient éliminées. L'aperçu aborde également l'état actuel de la législation relative aux déchets et la manière dont elle affecte l'environnement. Les technologies de valorisation durable et intelligente permettent des niveaux de recyclage élevés sans impact négatif sur l'environnement naturel.
MOTS CLÉS : tannerie, déchets, valorisation, durabilité, chrome

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INTRODUCTION

Today's business model, which is founded on the idea of “take-make-waste,” which is a continuous flow of energy and materials, leads to the fast utilization of natural resources and the creation of waste, the improper management of which damages the ecosystem. Thus, the sector needs solutions that will allow it to lessen its adverse environmental effects while meeting customers' demands [1]. The circular economy (CE), often known as the notion of environmental sustainability, is characterized by a cyclic movement of energy and materials, with an emphasis on refurbishment, restoring, and improving parts [2]. Using sources of renewable energy and reusing waste as additional resources, in simple terms. The concept of circular economy demonstrates more cost-effectiveness compared to the standard financial model due to its reduced reliance on power consumption and resources that are not renewable and more environmentally friendly (reuse of waste materials, reduced pollutant emissions). Its application promotes the growth of businesses through deploying novel technologies and increasing their reputations [3]. The manufacturing of leather is widely recognized as a highly polluting and resource-intensive sector. Approximately 25% of leather is derived from 100% raw materials, necessitating a water consumption ranging from 15,000 m^3 to 120,000 m^3. Consequently, this process results in the production of wastewater weighing between 15 and 50 mg, as well as solid waste ranging from 400 to 700 kg [4]. In addition to the aforementioned factors, it is important to consider the presence of smells, greenhouse gases (namely carbon dioxide, hydrogen sulfide, and ammonia), as well as organic compounds with volatile properties like amines, alkaline compounds, and hydrocarbons. The quantity of chemicals released is contingent upon the treatment methodology and technological processes employed for leather processing within a tannery [5]. The magnitude of the issue is illustrated by the fact that annual worldwide output of leather is predicted to reach 15 MT [4].

Tannery management of waste has hitherto solely involved landfilling and incomplete disposal due to financial constraints. When properly recycled, tannery scraps may serve as a vital component in advancing the cause of sustainable development. Waste disposal and pollution control expenses may be cut with CE plan adoption and leather waste valorization. Protein, fat, and water are the primary constituents of raw leather and processed waste, including trimmings, fleshings, and scouring (with the substances' moisture content reaching around 85%). [6]. The proteinaceous waste product possesses the potential to undergo hydrolysis by acidic, enzymatic or alkaline means, resulting in the extraction of collagen or gelatin. This process offers a cost-effective approach to get these substances, which can serve as valuable raw materials within the medicine and cosmetics sectors [7]. The use of tannery leftovers encompasses their potential for extracting oils and fats and their applicability in the creation of biodiesel [8]. The existing body of published material provides insights into potential avenues for the enhancing the value of waste generated by the leather industry. Several potential applications of leather waste have been identified in academic research. The scope of these applications involves the retrieval of activated carbon from waste derived from bio-collagen leather, with the purpose of purifying biogas, the fabrication of bio polymers from bovine hides, the development of sound-absorbing materials using leather collagen hydrolysates, the synthesis of surfactants being present from the protein portion of tanning wastes, and the creation of organic nitrogen-phosphorus fertilizers from the leather and chicken bones [9-12]. Producing ecological re-tanning compounds is another potential use for waste products from the leather manufacturing sector [13]. The oxidation of chrome Cr^{3+} to Cr^{6+} during the leather tanning process is a major contributor to pollution, and poses a health hazard to humans because of its oncogenic and cancer-causing properties. Contamination of soil and ground water can result from leaking chrome-tanned solid waste or high chrome contents in effluent [14]. Organic chelates can be used for successfully treating solid chromium leather waste, resulting in a 96% recovery rate [15]. Chromium can also be recovered with the help of acidic minerals like H_2SO_4, HNO_3, HCl etc. [16]. Thermal treatment of waste from tanneries can be employed as a means of extracting chrome in the form of Cr_2O_3, which can then be utilized in steel manufacturing within the metallurgy sector [14]. Tasca *et al*. conducted a study that focused on the environmental concerns associated with the tanning industry. The researchers specifically examined different procedures involved in the treatment of hides [17].

In their publication, Hu and his team offered a scholarly piece on the environmental treatment of tannery waste within the circular economy model [4]. Those researchers provided a comprehensive analysis of tannery pollutants and various dumping strategies, encompassing the decrease of effluent, solid garbage, salts and chrome. Pringle *et al*. [18] documented the difficulties associated with the implementation of circular economy (CE) principles within the leather industry. Their study primarily concentrated on the life cycle assessment of leather and the consequential waste produced throughout its manufacturing process. Additionally, they explored various recycling methods, including chemical, biological, and mechanical approaches, while also addressing the corresponding obstacles such as technological limitations, the value of retrieved substances, the existence of an additional market, and the economic feasibility of these recycling practices. A second researcher has proposed a way that could assist leather manufacturers achieve sustainability through optimization and improvement [19]. Specifically, Moktadir *et al*. addressed the problem of consumer consciousness and support from the government as predictors of the deployment of sustainable methods in leather items manufacturing in Bangladesh [20].

The objective of this review is to provide an overview of the most recent sustainable technical advancements pertaining to the leather sector, which is known for its high resource consumption. Additionally, this research aimed to examine the improvement made in managing waste from tanneries through the utilization of novel methods of treatment such as chemical, biological thermal, immobilization techniques. Using these techniques, several leather waste types have been converted to useful products like chromium, fats, gelatin vitamins, hydrolysate and minerals, biomass, and microbial waste products to promote circular economy. No contemporary study has focused specifically on the recycling of leather scraps, as far as we can recognize. In keeping with the principles of the sustainable or circular economy, these byproducts can be recycled for use in the tanning business or employed as a source of secondary raw materials in other industries (such as nutrients, biofuels, building, power, and pharmaceuticals). Entrepreneurs must balance the requirements of customers with ethical waste disposal in the face of rising global concerns about waste manufacturing and the consumption of basic supplies, calling for more study into the best possible method of tannery waste management with the hopes of learning how to most efficiently bring reused materials to the marketplace. Leather waste hydrolysates have potential as a replacement natural fertilizer ingredient. We have also examined the laws that are now binding, since their presence is crucial to the successful execution of massive amounts of technologies that are consistent with the CE plan.

THE WASTE GENERATED BY THE TANNING OPERATIONS

Tanneries generate wastes with a wide range of physical and chemical properties, which increases the complexity of waste management and necessitates a variety of approaches to trash recycling. There are several categories for the solid waste generated from tanned and untanned skins and hides. The quantity of wastewater (a liquid waste) produced is significantly higher. Figure 1 depicts several tanning waste streams and some of the ways in which this trash can be reused or recycled. To reduce the danger posed by ions of heavy metals along with other anions, and tannery residues can be processed using alternative valorization procedures that result in the extraction of high-value substances and components through recycling of materials. The features of various wastes, including their potential benefits and dangers, are shown in Table 1. The global legal categorization of waste generated by the leather industry is contingent upon its composition, particularly the presence of toxic elements such as chromium-containing substances and formaldehyde, as well as its production volume. The relevant legislation seeks to safeguard the well-being and protection of individuals and the natural surroundings by implementing guidelines pertaining to the containment and treatment of waste, stipulating emissions standards, and establishing thresholds for hazardous chemicals [21].

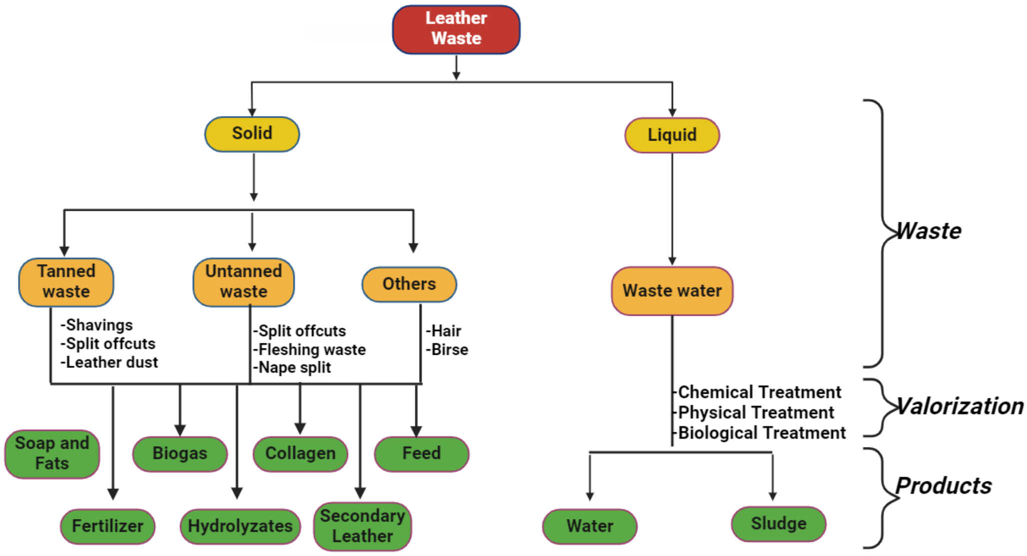

Figure 1. Tannery Byproducts and Potential Valorization Pathways (Source: *Authors compiled*)

Despite the absence of explicit rules pertaining to the tanning business within the European Union, this sector is subject to many requirements concerning the application of chemical compounds, animal by-products, specified dangerous compounds, as well as the promotion of those substances. The introduction of the Industrial Emissions Directive marked the implementation of a comprehensive strategy that emphasizes the integration and evaluation of the effects of commercial pollution and waste on the whole of the ecosystem [22]. Consequently, the defining of emission circumstances and levels in accordance with Best Available Techniques (BAT) has been reinforced. The pertinent papers include Regulation (EC) 1069/2009, the European Regulation on Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) and Commission Regulation (EU) 142/2011 [23, 24]. The European Trash Catalogue, which is outlined in the EU Commission Decision, serves as the primary reference for the generation of waste. According to the legislation, tannery related waste is categorized under label 04.01, which pertains to waste related to the tanning sector. The regulation of the European Union also provides explicit definitions for the maximum permissible levels of certain substances and components in leather goods. The inclusion of polychlorinated triphenyls (PCTs), arsenic, organotin chemicals as well as polychlorinated biphenyls (PCBs), and is strictly forbidden in tanning industry [21]. The highest recorded levels of heavy metals, namely Cd, Cr^{+6}, and Pb, are 100, 3, and 90 mg/kg, correspondingly. Particular attention is given to minimizing the usage of organic chemicals, namely pentachlorophenol, formaldehyde and azo dyes, due to their inherent hazards, especially to human health [17].

Table 1: Characterization of tannery waste

SL.	Waste/Residue	Explanation	Precious Component	Corresponding Risk	Methods of valorization	Prospective products after valorization	Reference
01	Effluents and wastewater	Liquid residue of leather treatment and pretreatment	Water	Chemicals such as colorful substances, sodium chloride, sulphate, inorganic and organic chemicals, and hazardous metallic substances, particularly Chromium derivatives.	Processes like filtration, coagulation, and precipitation are used to treat wastewater.	Sludge and clean water	[25], [13], [26]
02	Sludge from Tannery	The management of solid trash arising from the treatment of effluent and wastewater.	Mg, Ca	organic substances, coloring agents, chromium, and microorganisms that are harmful	burning, hydrolysis, leaching, and putting trash in landfills	Cinders/ash	[16], [27], [28]
03	Cuttings and splits	substantial waste produced during the shaping and cutting of leather that cannot be reused	Fat and protein	Organic materials, including colors and tanning substances, are commonly associated with the element chromium	digestion, combustion, and hydrolysis	Active carbon, ash, and collagen hydrolysate	[29], [30], [31]
04	Shavings waste	waste products from cutting and shaping leather.	collagen	chromium, tanning agents, and dyes	Basic hydrolysis	Hydrolyzed protein from collagen with less Cr	[32], [33], [34]
05	Buffing dust	Hazardous solid waste, consisting of micro fine powder of collagenous fibrils, is produced during the leather buffing process.	collagen	Synthetic fat, color, tanning substances, and Chromium	digestion by anaerobic processes, hydrolysis, and burning	collagen hydrolysate and activated carbon	[35], [36], [37]
06	Waste of fleshing	waste from the tanning process of hides that is made from the skin remaining after the tissue attached to the hide of the animal is removed	Fat and protein	NaCl, tanning substance	burning, hydrolysis, and extraction of fat	Soap, biofuel, and hydrolysate of proteins	[38], [39], [40]
07	Hair	Hair pulping results in the generation of solid garbage.	keratin	Not found	Decomposition, combustion, and land filling	Activated carbon, ash, and keratin hydrolysate	[41], [42], [43]

The case study of the leather sector in Bangladesh was employed to illustrate the many obstacles that contribute to suboptimal outcomes in the adoption and implementation of environmentally friendly technology [44]. Notwithstanding the implementation of novel facilities for treating wastewater, the existence of dated equipment and the utilization of significant quantities of substances presented formidable challenges. The assistance for the adoption of sustainable supply-chain management techniques in poor nations is lacking in both scientific and financial aspects from the state [45]. Insufficiently trained personnel, lacking awareness of environmental hazards, are employed in the operation of ineffective facilities with excessive emissions that fail to fulfill regulatory standards [46]. It is noteworthy that the absence of pressure exerted by globally recognized organizations fails to promote the promotion of cleaner manufacturing and minimized waste within the tanning sector.

THE ENVIRONMENTAL EFFECTS OF THE TANNING ACTIVITY

Enhancing the environmental quality via the use of cleaner manufacturing practices has a positive impact on the overall well-being and health of human populations. The achievement of long-term sustainability in the tanning industry requires a comprehensive strategy that encompasses several dimensions, including technological, financial, environmental, institutional, social, and legal elements [47]. The tanning business is known for generating significant quantities of trash, which, while not consistently, is often categorized as harmful. The heavy metals, organotin chemicals, formalin, PCBs, Azo dyes, PCTs, and phthalates are often cited as notable examples. These compounds often result in impairment of the kidneys, lungs, urinary, liver, and genital systems, as well as causing conjunctivitis and skin irritation. Their concentrations in the plasma and bloodstream are measured to detect their high levels [48]. Chromium, namely in the form of Cr^{6+}, is present in significant quantities within the effluent generated by the leather sector. This particular form of chrome exhibits notable attributes such as elevated mobility, assimilability and bioavailability [49]. Upon introduction into water and soil, this substance readily integrates into the ecological food web, hence exerting a deleterious impact. It has the potential to impede or hinder plant development, while also instigating various ailments in humans as well as animals. At high doses, it may potentially induce fatality [50].

Table 2 presents the various techniques used for the removal of Cr^{6+} from effluent, along with their respective efficiencies. Table 2 illustrates a wide array of effective techniques for the removal of chromium from tannery effluent. The efficiency of the system exhibits a range of values, often falling within the interval of 90% to 100%. Every approach has advantages and disadvantages. The process of sorbing chromium onto activated carbon or attaching it to organic matter by the process of biosorption akin to biological accumulation in fungus culture, yields significant removal rates. However, this approach presents a challenge in terms of chrome retrieval from sorbents or effective management of the sorbent material.

Table 2: The removal of Cr^{6+} from wastewater generated during the tanning process

SL	Cr^{6+} concentration before treatment (mg/L)	Cr^{6+} concentration after treatment (mg/L)	Removal Percentage	Removing Technique	Reference
01	100	9.50	90.5%	Activated carbon assisted sorption	[51]
02	2700	0	100%	Electric coagulation	[52]
03	2	0	100%	Photo-electrocatalysis	[53]
04	2920	3.46	99.9%	Biosorption	[54]
05	12.26	0.10	99.9%	Fungus Consortium bioremediation	[55]
06	544	19.00	96.5%	Electroplating	[56]
07	5010	75	98.5%	Hydroxides precipitation	[57]

The aforementioned approaches are characterized by their extended duration, which therefore renders them economically inefficient. The use of precipitating techniques necessitates the introduction of hydroxides, which result in the extraction of chromium and subsequent enrichment of alkali metals in the effluent. The use of electricity in methods that facilitate the precipitation of chromium in either metallic or oxide state is deserving of significant notice. By using this method, the retrieval and reintroduction of chromium into the production cycle may be effectively achieved, aligning with the principles of cleaner manufacturing. However, because to the exorbitant cost of power, the procedure is not economically viable [58]. CH_2O, primarily employed in the resinous state for the purposes of tanning and the preservation of leather, has carcinogenic characteristics. Consequently, it is essential to diminish or remove its usage and substitute it with substances such as mimosa extract, gallic acid or vegetable polyphenols. The proper handling of discarded or surplus leather necessitates the appropriate handling of its colors, particularly those belonging to the Azo group. The use of tanning agents is regulated, and the imposed restrictions on their usage are somewhat stringent. Non-harmful vegetable dyes have the potential to serve as suitable substitutes. The pigments found in flowers, fruits, and vegetables, notably carotenes, have a significant capacity for coloration [59]. In the event where synthetic dyes are the only means of coloring leather, it becomes necessary to subject the leather to decolorization after its usage, which may be achieved by the enzyme-mediated activity of fungus [60].

Furthermore, conventional techniques may be used to extract colors from leather, followed by the treatment of the resulting wastewater by processes such as adsorption using active carbon substances, flocculation, coagulation, and ion exchange for example [61]. The available literature also provides evidence of several additional substances, when employed in the process of tanning, may elicit detrimental impacts on both human health and the environment. Phthalates function as plasticizers, hence preventing the occurrence of fractures in crucial regions of leather. These chemicals have been shown to induce reproductive complications in both males and females. During the concluding phase of manufacturing, tanneries use biocides as a means of inhibiting the proliferation of microflora. Allergy or irritation to the skin may be induced by these substances, while high dosages may result in symptoms such as migraine or vertigo [48]. At the moment, the generation of energy is a major producer of greenhouse gasses, whereas recycling of materials and energy occurs at relatively low levels. Wastewater treatment, namely waste management, ranks as the second most energy-intensive procedure [62]. Similar to waste treatment, the process of tanning leather is characterized by its significant energy use. The leather tanning phase, including several discrete procedures conducted at reduced temperatures, accounts for roughly 90 percent of the total energy use [19]. The existing research indicates that the predominant methods used for recovering energy from solid tannery waste are gasification, hydrothermal treatment carbonation, and anaerobic fermentation [63]. Special consideration should be given to the potential risks associated with hazardous compounds, such as chrome, colors, and formaldehyde, due to their adverse effects on waste processing and the use of resultant intermediate materials. However, it is important to note that the storage of these chemicals might potentially result in leakage, leading to significant environmental pollution and the potential integration of certain compounds into the food chain. Furthermore, the aforementioned compounds provide a potential hazard to those employed in tanneries, since they may result in the development of skin disorders and respiratory difficulties, despite the use of protective clothing and footwear [64].

TECHNIQUES FOR THE MANAGEMENT OF BY-PRODUCTS DERIVED FROM THE LEATHER SECTOR

Through Chemical Methods

The first tanning process results in the generation of substantial quantities of solid waste. This includes around 7-8% of raw, unprocessed scraps. Proteins make up the bulk of these elements. The conversion of this particular waste into useful goods may be achieved using either acidic [65] or alkaline hydrolysis [32]. Proteins hydrolysate is derived via the application of acetic acid, with an ultimate concentration of 1.5 M, to untanned raw trimmings. The optimal process efficiency, which reaches around 80-85%, is achieved at a temperature of 80°C [31]. In a study conducted by Khatoon *et al*. several techniques were examined and compared in order to isolate protein constituents from chromium leather garbage. Protein and amino acid extraction was performed using alkaline techniques including sodium hydroxide (NaOH), calcium oxide (CaO), and magnesium oxide (MgO), as well as an acidic process utilizing sulfuric acid (H_2SO_4). The extraction process is adversely impacted by both elevated quantities of extractants and increased process temperature, resulting in the decomposition of proteins [66]. Like other heavy metals, chromium undergoes precipitation as $Cr(OH)_3$ under alkaline circumstances. The precipitate is collected using filter paper, followed by the separation of insoluble proteins by a reduction in temperatures to 4 °C. Optimal outcomes are achieved by using H_2SO_4 at a temperature of 40 °C and NaOH at 50 °C temperature. The agriculture industry has already been identified as a primary beneficiary of this invention, which includes things like fish food, feed for chickens, and organic compost. Important consideration must also be given to the recovery of amino acids from hide treatment wastewater produced during the unhairing-liming, soaking and curing stages. The protein portion obtained from the effluent is precipitated by using acidic conditions, specifically 2M H_2SO_4. This precipitated fraction is then exposed to a degreasing process using CH_2Cl_2 for a duration of 5 hours. Following the degreasing step, the protein fraction is hydrolyzed in the existence of HCl for a period of 24 hours. This hydrolysis process serves to minimize tannery waste and produce agents that are ecologically benign. The acetylation of a mixture of amino acids is the process that results in the production of surfactants [10]. Polypeptides were also extracted from the leather dust created during the polishing process. In an autoclave, NH_4OH is used to hydrolyze the dehydrated wastes (C_2HCl_3). There was a 55% increase in protein production. The addition enhanced the material's primary physical qualities [67].

The utilization of leather waste from processing as an economical collagen source is noteworthy due to its numerous uses in the cosmetic and medical sectors, as well as its potential to increase the mechanical qualities of composites [7, 68]. The type I collagen is the prevailing constituent found in the dermal layer of all animal skins, serving as a fundamental component in the formation of bone, tendon, and many types of connective tissues [69]. The solubilization of the skin matrix component was conducted using acetic acid and propionic at a concentration of 0.5 M and a temperature of 4 °C. The effectiveness of collagen extraction was found to be 94% and 85% in the two respective experiments. The component separated by each acid belonged to type 1 and shared similar chemical and physical characteristics [7]. Collagen-based waste-derived hybrid composites have been shown to have excellent biocompatibility. Due to their characteristics, they may be useful in the field of biomedicine [70]. Tannery waste collagen is used in several publications. Collagen hydrolysis produces sound-absorbing nanofibers. First, alkaline, acidic, and enzymatic hydrolyses occur. The efficiency research showed that alkaline hydrolysis yielded the most (64%) whereas acid hydrolysis enzymes did not impact the process. After electrically spinning with polyvinyl alcohol, polyacrylonitrile fills the hydrolysate layers. Acoustic studies showed that the composite material absorbed 1000–2500 Hz sound [71]. An additional illustration entailed the utilization of extracted collagen to extend the duration of gypsum's solidification process. Hydrolysis of tannery waste occurred at 90 °C in sodium hydroxide solution. The method was 85% efficient. Flocculation and diatomaceous earth eliminated chromium. Additional component lengthened gypsum setting time but decreased strength [72]. The production of alumina composites involved the use of collagen that was extracted by the process of acetic acid hydrolysis. Initially, the process of removing chrome in leather wastes involves the utilization of strong sulfuric acid. The samples that have been stripped are submerged in a mixture of HCl, ethylenediaminetetraacetic acid (EDTA), and C_2H_5OH, with a pH level of 8 for a duration of 3 days. Subsequently, the samples undergo acid hydrolysis for a period of 24 hours. The collagen powder obtained had a chromium concentration of around 6%. The composite material was subjected to the hybrid casting process after being mixed with alumina. The composite material exhibited a notable enhancement in both tensile strength and its hardness, with increases of 40% and 55% correspondingly [73]. Limed fleshing leftovers, which encompass skin tissue and the muscles, are abundant in protein content and constitute approximately 60-70% of the waste generated by tanneries. Traditionally, these residues undergo thermal, chemical, and enzymatic treatments to produce feed additives, glue, or biogas [74, 75]. The work conducted by Ammasi *et al*. introduced a novel technique with the objective of utilizing treated with lime fleshing residues to provide a feasible source of polypeptides to improve the quality of leather surfaces. To do this, an alkaline protease isolated from *Bacillus* crolab5468 is used in an enzymatic hydrolysis reaction. The garbage that was formerly produced is subjected to hydrolysis for a duration of 60 minutes at a temperature of 35°C, while the enzymes present in the waste are rendered inactive at 90°C temperature. The acquired polypeptides were tested on the skin of goat to determine their effect. Comparative analysis revealed notable enhancements in both visual aesthetics and mechanical strength characteristics when comparing treated leather samples to their untreated counterparts [66]. Protease uses the nitrogen and carbon in fleshing waste to digest the hide and remove the fur [76]. Lipids from flushing leftovers can be utilized to make biofuels [77]. The possibility of using tannery waste in the manufacture of biodiesel was also highlighted by Yuliana *et al*. [78]. Supercritical ethanol is used for lipid extraction. A remarkable output of 98 percent was accomplished.

Several research studies have identified novel avenues for the use of leather waste treatment. In their study, Yoseph *et al*. [79] demonstrated a methodology for the extraction of elastin, a crucial constituent of connection tissue that has substantial importance in the formulation of lotions, ointments, and anti-aging goods. They focused on isolating elastin from unprocessed cuttings. The mechanism involved in the extraction of this particular constituent from tannery effluents is inadequately comprehended. The waste materials are immersed in a mixture containing NaOH (5%), CaO (10%) and NaCl (5%) for a duration of 8 hours. The liquid portion is isolated, subjected to purification techniques, and subsequently subjected to evaporation. Insoluble elastin is acquired by the process of autoclaving, which is conducted under certain conditions consisting of a temperature of 120 °C, a pressure of 15 psi, and a duration of 20 hours. Since elastin has a specific amino acid composition, the characterization technique verified the accurate separation of proteins. The utilization of waste as a potential resource for re-tanning purposes is a viable application. The composition of these compounds mostly relies on formaldehyde, with concentrations reaching up to 50 mg per kilogram in leather. The researchers suggested the employing of a substance derived from discarded waste from tanneries cuttings. The residue underwent pretreatment by immersion in a hydrogen peroxide alkaline solution consisting of 7.5% w/w NaOH and 10% w/w H_2O_2 for a duration of 6 hours. The material underwent thermal hydrolysis at a temperature of 100°C for a duration of 5 hours. The product underwent neutralization using an acid that is organic with a pH of 8.5, followed by the process of spray drying. A comparative re-tanning experiment was done using a phenol condensate-based product. The test results demonstrated enhanced leather color intensity and heightened resilience to fracturing [13]. In their study, Majee *et al*. [11] introduced a novel fertilizer formulation that incorporates tannery waste as a constituent. They provided a detailed account of the methodology involved in the production of a NPK-based fertilizer utilizing, chicken bones, blue leather, and hyacinth water. The utilization of tannery trash, which has undergone a two-step alkaline hydrolysis process to remove chromium, is employed as a nitrogenous resource. The material undergoes acid hydrolysis, resulting in the formation of solid collagen. This collagen is subsequently pulverized and mixed with the meal of bones and dehydrated plant biomass. The study saw a 45% increase in soil nitrogen content when compared to unfertilized soil, and a 19% increase compared to soil treated with industrial fertilizer.

Chemical processes, such as the extraction process, hydrolysis, and enzyme-mediated hydrolysis are primarily employed for the valorization of leather waste. The provided illustrations demonstrate the process of isolating proteins or lipids and highlight the potential applications of the obtained components. The presentation of the management of by-products, namely chromium sludge that poses environmental risks, is not consistently addressed in relation to the enhancing the value of chrome leather waste. An innovative strategy involves utilizing waste materials as a viable resource for the production of means utilized in leather treating, and a supply of ammonium in macro element fertilizers. That specific recycling methodology aligns with the underlying principles of an economy that is circular and environmentally-friendly innovations.

Through Biological Methods

Instead of sending waste that is organic to a landfill, it can be composted for biological degradation [80]. The implementation of aerobic stabilizing techniques on tannery sludge offers significant benefits in terms of waste mass reduction, emissions mitigation, and prevention of landfill leakage. This approach is crucial for achieving ecological disposal practices [81]. The utilization of compost derived from a combination of tannery sludge and agricultural waste, when employed as a fertilizer for the purpose of cultivating ornamental peppers, is being investigated. There was a substantial augmentation in the quantity of leaves, vegetables and fruits, and chlorophyll content inside the leaves [82]. Vermicomposting is a biological process that facilitates the degradation and stabilization of organic materials, resulting in the production of a fertilizer that is abundant in nutrients. The remediation of sludge from tanneries through the utilization of earthworms necessitates the incorporation of other substances, such as manure, in order to diminish the concentration of chromium ions present in the initial material. This step is crucial as chromium is known to be harmful to earthworms. Co-vermicomposting is a method of composting that involves the simultaneous use of earthworms and microorganisms to decompose [83]. The utilization of vermicompost derived from the fleshing of waste from tanneries resulted in a notable enhancement in crop productivity, exemplified by a growth increase of over 10% in tomato plants [84]. Plant growth was stimulated by vermicompost made from tannery garbage, but there was no discernible rise in chromium levels in lovely bell pepper plants [85]. Nevertheless, the extended utilization of compost presents a potential risk of chromium ion buildup inside the soil. The findings of a decade-long investigation on the utilization of compost tannery waste revealed alterations in soil characteristics. The increase in the amount of organic elements and macroelements has a favorable outcome. Simultaneously, there is an increase in the concentration of chrome in the ground and a corresponding rise in its pH, leading to alterations in the composition of soil microflora. The period of highest magnitude in the augmentation of chromium concentration within the soil occurred within the initial five-year timeframe of the experimental study [86].

The process of breaking down organic materials by anaerobic bacteria is known as anaerobic digestion. Biogas is generated as a carrier of energy, while the resulting sludge, characterized by its elevated nutritional contents, can be utilized as a fertilizer. Anaerobic digestion (AD) has demonstrated promising results in the efficient breakdown of waste products generated by tanneries. Research conducted under semi-pilot settings has demonstrated that the utilization of biogas derived from this particular method has the potential to decrease energy usage by around 7% [87]. It is recommended to include tannery residues into co-digestion with other residues, mostly due to their elevated nitrogen-rich air content and the imperative to maintain an appropriate carbon-to-nitrogen proportion of 25:1 [88]. The inclusion of supplementary digestive components results in a reduction in the concentration of unwanted contaminants, such as chromium. Research has demonstrated that the digestion together of scraps and sludge from tanneries exhibits a significant reduction in power usage, surpassing 75% [89]. The existence of sulfides in leather fleshing waste necessitates cleaning prior to liquid entry into digesters, since this might raise hydrogen sulfide content in the production of biogas [90]. Microbial biological degradation has been identified as a viable approach for the breakdown of specific waste materials generated by the leather industry. The research findings indicate that *Brevibacterium luteolum* MTCC 5982 is a microbe with the ability to breakdown keratin derived from goat hair in an efficient manner. The highest level of hydrolysis was attained at the end of a 72-hour period, demonstrating an efficiency rate of 80% [41]. The degradation of high in protein chromium shavings may be effectively accomplished by *Bacillus subtilis* P13, a strain known for its production of keratinolytic serine protease. This particular strain exhibits a substantial capacity for enzymatic production, wherein a significant portion of the resulting product may be effectively allocated for pre-tanning applications [91].

Elevated levels of chrome in garbage have the potential to impede microbial activities; nonetheless, it is worth noting that organisms possess the ability to acclimate to platforms that incorporate this particular metal [92].

Microbial populations exposed to elevated levels of chromium have been observed to develop adaptive mechanisms, including biosorption, which involves the attachment of metal ions to cell wall polymers, and bioaccumulation, a complex process by which cells actively accumulate ions within their intracellular environment. The microbial breakdown of fleshing by *Clostridium limosum* not only led to a reduction in the amount of contaminants present, but also resulted in the concomitant synthesis of an extrinsic acid metalloprotease [93]. In a similar vein, *Synergistes* sp. has the capability to synthesize aspartate proteases. Proteases, being enzymatic catalysts, provide extensive utility throughout many sectors of the industrial landscape. The production in this particular scenario serves as an additional benefit to waste treatment [94]. The process of bioleaching has demonstrated its efficacy in the removal of chrome ions from tanning sewage [95]. The solubilization of chromium ions is facilitated by acid-producing microbes, specifically *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans* and the resulting sludge, once separated, can be utilized in agricultural applications. By carefully selecting appropriate bioleaching circumstances, it is possible to achieve a significant increase in the leachability of chrome from waste products. In fact, for tannery sludge, the leachability can reach levels as high as 98% [96].

Finally, it can be said that valorization of tannery waste via biological means can be an intriguing alternate to conventional approaches. These technologies are crucial to the leather industry's waste management strategy since they allow for the effective recycling of valuable substances (organic substances, chromium, and fertilizer ingredients) and energy (biogas), as well as the development of new goods (enzymes).

Through Immobilization Techniques

Composites may contain waste tannery materials [97]. Cracking in asphalt is reduced when scraps of chrome-tanned leather are embedded in the material [98]. In the context of reusing tannery waste, leather-fiber composites were created through the blending of leather waste with artificial and organic fibers. The resulting yarn exhibited a high level of density, rendering it well-suited for utilization in the garment sector [35]. Insulation and acoustic panels made from leather scraps or their isolated components are among the “green building materials” now in use. The dried form of chromium chips and buffing dust has a very low heat conductivity and does not compromise the strength of building materials [99]. The thermodynamic simulations conducted on a building that was insulated using panels composed of a blend of leather (consisting of cleaning dust and chromium parts) and carpenter's trash have substantiated its significant thermal shielding efficacy. The examination of relaxation levels and usage of energy provides evidence that these panels have the potential to compete commercially with other substances such as polystyrene. The implementation of more than 7 mm in thickness coating of buffing dust results in a reduction of over 50% in the yearly energy usage [100]. Tudose *et al*. [101] demonstrated that the utilization of leather waste can yield materials possessing favorable thermo-insulating characteristics. The researchers conducted an analysis on the diffusion of heat properties of seven materials derived from tannery and woolen waste in their study. The untreated wool materials demonstrated the lowest values ($6.0x10^{-8}$ m^2/s), followed by powder leather waste ($8.5x10^{-8}$ m^2/s).

The performed feasibility research and environmental impact analysis have affirmed the suitability and satisfactory insulation qualities of the insulation material derived from mixed leather scraps, as well as the readily accessible insulation board composed of polyurethane. However, the determination of which technology possesses a more substantial environmental impact has not been reached. Simultaneously, the substantial upside potential of waste from tanneries was effectively showcased, underscoring the imperative for conducting comprehensive economic evaluations [102].

The examples shown demonstrate how, even in the absence of further processing, tannery waste treatment can add value to novel composite materials. The literature review reveals a lack of comprehensive understanding on the ecological and economic dimensions associated with the production of this particular material.

Through Thermal Methods

The utilization of solid leather waste as a potential feedstock for the production of energy is supported by its notable high higher heating value (HHV) of around 16 MJ/kg. Burning and pyrolysis are widely recognized as significant thermal methods of treatment for these wastes. The process of burning leather trash, characterized by its elevated nitrogen composition, results in the release of substantial quantities of nitrogen oxides (NOX). The co-incineration of plant materials, such as wood pellets, results in reduced emissions mostly due to their significantly lower nitrogen concentration. This reduction in nitrogen content ensures that the emissions of nitrogen oxides (NOX) meet the required emission criteria. It is necessary to conduct monitoring of the concentration of deleterious organic chemicals present in gases from the combustion process [103]. Energy and chrome substances can be recovered using pyrolysis heat treatment, which is believed to boost tannery savings (by a number of millions of dollars annually) [104]. When comparing combustion to pyrolysis, it is evident that the latter is highly influenced by many parameters such as temperature and heating rate. As a result, pyrolysis generates gas and liquid byproducts with significant energy content, making them suitable for use as fuel [28]. Gaseous, liquid, and solid end product mass ratios are greatly impacted by the ultimate pyrolysis temperature. At temperatures under 450 °C, the solid phase dominates, indicating inadequate breakdown of organic material. Additionally, a high gas phase with significant CO_2 concentration is detected. Raising the temperature around 500 °C increases the liquid phase share. While gas production declines with heat, calorific value of this increases because of greater hydrogen and methane concentration, achieving about 9.50 MJ/Nm^3 at a temperature of 500 °C [105].

Waste materials can also be gasified to produce energy. Syngas, the resultant higher-energy byproduct of this procedure, may be burned and used as a fuel replacement in tanneries [106]. During heat operations, the process of immobilizing Cr occurs in a solid state, hence facilitating its safe disposal. At elevated temperatures during combustion, there exists a potential hazard of transforming Cr^{3+} into the toxic Cr^{6+}. It is noteworthy that chromium undergoes a shift in its state of oxidation to Cr(VI) when exposed to high temperatures and oxidizing chemicals. To prevent this transition, it is advisable to do pyrolysis at temperatures below 600 °C [107]. The waste generated during chrome tanning of leather mostly comprises protein collagen and chromium. After subjecting the trash to pyrolysis at temperatures of 700 and 800 °C, chromium (Cr) was found to be abundant in the carbonate compound as Cr^{3+} [108]. The carbon matrix is strongly connected to trivalent chromium compounds. The results of leaching tests demonstrated that the trash was stable and did not leak into the surroundings [109]. The amounts of carbon and chrome found in tannery waste's carbonized pyrolysis products make them a suitable replacement for fossil coal in steelmaking. Carbonized leather scraps were used in place of coal in the production of iron ore pellets. By including leather scraps into the mix, we were able to boost the pellets' compressive property and Cr^{3+} content, resulting in a 50% recuperation of metal rate [110].

Activated carbons derived from leather garbage possess a notable capacity for adsorption due to their substantial porosity, rendering them suitable for a diverse range of usages. One of the most common environmental uses is for filtering out hazardous chemical compounds and dyes from water and air [111]. In addition to their application as adsorbent for aquatic contaminants, activated carbons enriched with gaseous nitrogen can function as electrode materials thanks to their high and consistent charging and discharging capability [112-114]. Other intriguing materials for energy storage systems, especially electrode materials, are multilayer porous graphitic carbon substances produced from leather waste [115]. Tannery garbage might be utilized to create heteroatom enriched aerogels made of carbon by activated burning, which could then be employed in electrode production [116]. Instead of using hazardous carbon black, rubber compound fillers may be made from carbons that are activated formed on CaO via limed fleshing pyrolysis [117]. Filler substances for lighter blocks of cement can be made from carbonated buffing powder from the leather industry. The addition of iron nanoparticles prevented Cr^{3+} from being converted to Cr^{6+}, hence enhancing the product's mechanical characteristics even more [118].

Their wide range of uses demonstrates the great potential of activated carbons, which are produced by pyrolyzing tannery waste. The potential applications are enhanced as waste usage becomes more efficient, aligning with the principles of a closed-loop economy and significantly contributing to the reduction of pollution in the environment.

Other Methods (Miscellaneous)

The utilization of tannery waste that contains chromium has the potential to be transformed into ceramic pigment. In order to get the desired outcome, waste material is subjected to a process of washing before to being subjected to temperatures exceeding 1000 °C. This process aims to produce a permanent greenish chromium pigment suitable for use in ceramics products [119]. The addition of minerals during vitrifying plasma results in a glass-like substance with minimal component leachability. The trash can be stacked away or even utilized as filler in building projects [120]. Reinforced biological composites made from leather scraps and cement have useful mechanical qualities and can be used in the building industry [121]. Bricks and other ceramics can be made from a mixture of tannery sewage and clay. Immobilized in a rigid matrix, chrome is harmless to ecosystems [122]. The utilization of leather waste generated by the tanning industry has the potential to enhance the efficacy of composite material manufacturing processes. The collagen structure that makes up leather has a multitude of polar groups that facilitate the formation of bonds with thermoplastic polymers. The incorporation of leather waste, namely fragments ranging from 10 to 500 µm, at a concentration of 7 to 23%, into thermoplastic starch leads to enhanced mechanical properties and increased longevity of the resulting composites [123]. The utilization of composites comprising polycaprolactone and residual leather particles exhibiting excellent characteristics holds potential for application within the footwear or leather products industry. The utilization of waste leather in the reinforcement of the matrix material offers a fully compostable solution that eliminates the need for high processing temperatures. This is particularly advantageous as it avoids the conversion of chromium in its trivalent state Cr^{3+} to its hexavalent state Cr^{6+} [124]. The effective dispersion of waste fibers inside the matrix is facilitated by their separation into individual fibers. This can be accomplished by the utilization of Solid-State Shear Milling (S3M) technology. As a direct consequence, the material exhibits enhanced its mechanical qualities [125]. Fabricating composites with aqueous polyurethanes resulted in an increase in mechanical characteristics. Hydrogen bonding within the matrix and the garbage cause these characteristics [72]. Polymers like polypropylene can be combined with chromium flakes to create acoustically absorbent composites. Over 90% sound attenuation was shown by Hemalatha *et al*. in the mid-frequency band [126].

The high chromium content of tanning effluent makes it a major environmental hazard. Ultrafiltration (which removes colloids and suspended particles), nano-filtration, and reverse osmosis (which removes ions containing chromium) are all membrane technologies that can be used to treat such streams effectively. High efficiency chromium recovery from effluent streams is guaranteed by carefully selecting separating parameters (pressure, the velocity of flow, and acidity) [127]. In order to retrieve chrome with a high selection effectiveness (above

90%), the membranes used for microfiltration might have their surfaces modified with substances like chitosan [128]. In addition to reducing COD and nitrogen-based pollutants, electrical membrane methods are also successful in recovering chromium. The retention rate of COD is between 87-92% and is affected by the kind of electrode employed in the electrocoagulation/ electrodialysis process, whereas NH3-N and chromium are removed with a 100% efficiency. The end result had the same levels of contamination as regular drinking water [129]. The utilization of a dual approach using microfiltration and a combination of reverse osmosis techniques to handle the treatment of wastewater from tanneries has been seen to yield a wastewater that has been treated that exhibits favorable suitability for application in aquaculture. This assertion is supported by scientific investigations conducted on the snail species *Pila globosa*, which serves as a reliable biomarker for assessing oxidative stress levels [130].

TANNING SECTOR AND THE CIRCULAR ECONOMY

The process of leather production results in significant quantities of waste, which might potentially serve as valuable resources for many sectors (see Figure 2). The available literature demonstrates that tanning residues undergo processing in order to generate re-tanning ingredients [13]. The aforementioned waste materials serve as a reservoir of chromium, which may be effectively repurposed in the manufacturing of leather following suitable treatment methods. The creation of fertilizer from tannery byproducts is an emerging method of waste-free manufacturing. In order to create a nitrogen-rich byproduct that may be used as an ingredient of NPK fertilizers, leather scraps are hydrolyzed in acidic or alkaline solutions [11]. The procedure allows for the elimination of chrome, the amount of which is restricted by law from fertilizer formulas [131]. Hydrolysis allows for the generation of a fertilizer byproduct and a chrome content, both of which have value and fit into the "circular economy" framework. The use of chemical fertilizers can be reduced or eliminated if this trash is recycled. This strategy is an eco-friendlier option. There are several upsides to implementing the strategies of environmentally friendly manufacturing and the circular economy. However, financial evaluation and technological feasibility assessment are just two of the many processes needed to put these approaches into action.

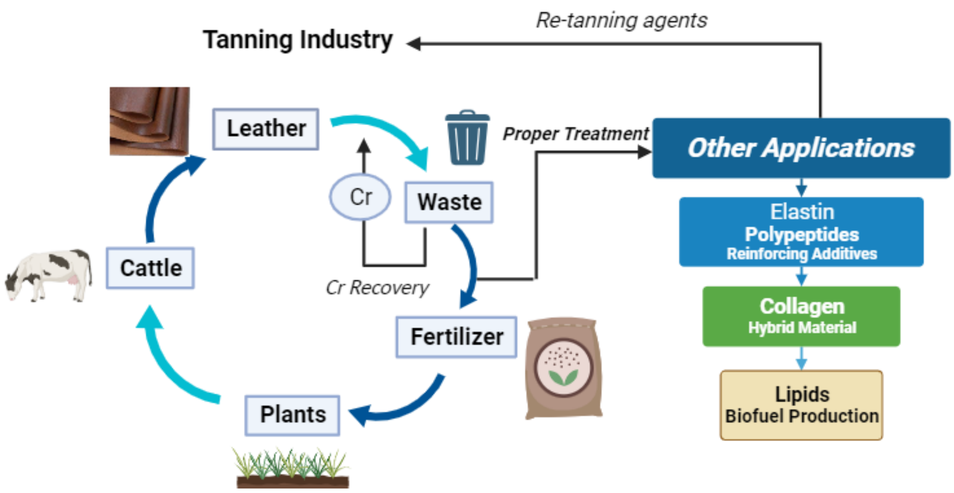

Figure 2. Concept of circular economy in leather sector (*Source: Authors compiled*)

CONCLUSION AND INSIGHTS

Waste from the leather tanning process presents a difficult management challenge due to its varied qualities. When it comes to the environment, nothing beats dumping trash in a landfill. By-products from the tanning industry can be dried, burned, pyrolyzed, and gasified; they can also be treated thermally or mechanically, as in briquetting; they may be utilized as a basis for methane fermentation. Novel biological processes include those that generate digestate, biogas, gelatin hydrolysate, fat, or fertilizers. Anaerobic digestion digestate can be employed for plant nutrition, and fermentation of methane allows for recovery of energy. The presence of chromium presents a significant challenge. Thankfully, there exist many techniques for the treatment of waste from tanning factories that contains the aforementioned ingredient. The preservation and cremation of tannery residues do not effectively mitigate the potential for secondary environmental contamination caused by chromium compounds. In order to mitigate this issue, several hydrolytic procedures such as alkaline, acidic, enzymatic, or mixed approaches are employed. One limitation of this approach is to the degradation of the collagen structure with subsequent depletion seen in the hydrolysate. Organic acid salts have the potential to serve as a viable option for the retrieval of chrome substances, hence facilitating the conservation of the collagen matrices. This preservation process is particularly valuable in the context of producing collagen hydrolysates.

The process of collagen extraction holds significant importance within the chemical, food, and pharmaceutical sectors. There is a need to improve the effectiveness of collagen regeneration. From a quantitative point of view, the primary concern within the leather business revolves around the presence of unprocessed leather and gelatin byproducts. The efficacy of these goods exhibits variability and is contingent upon the technical process and its respective phases. The practical application of by-products derived from wet tanning operations is limited. There is a need to develop a system for controlling chromium particles and chromium splits, which are substances generated during the latter phases of leather manufacturing. The valorization of trimmings of polished leather necessitates the implementation of appropriate design procedures.

Only by shifting away from a linear economy and toward an enclosed-loop economy, which ensures sustainable and less pollution, will the tanning industry be able to lessen its destructive influence on the environment and its high rate of energy consumption. It is extremely important for the leather business to have effective waste management since valuable components may be salvaged and recycled either within the same industry (chrome) or in other areas of the manufacturing sector (such as collagen, nutrients, energy carriers). The implementation of waste-free technology, in which every waste flow may be reused, is the largest obstacle. All material streams should be valorized, and new sustainable technologies should be compatible with the structure of waste management. Wastes bearing harmful chemicals such coloring agents, chromium, formaldehyde and phthalates must be changed immediately. It is scientifically demonstrated that this has a negative effect on the ecosystem as a whole. Natural dyes are one example of a biodegradable and safer option that should be explored. As a result, tannery staff and leather consumers will be safer and less pollutants will be released into the atmosphere. This review study is anticipated to provide guidance for future researchers who are fascinated in conducting studies during this interesting realm of wealth generation from leather waste.

Authors' Contributions

Md. Abdus Shabur: Conceptualization, Methodology, Writing – Original draft preparation. Md. Amjad Hossain: Reviewing, Editing and supervision.

Ethical Statement

Authors confirmed that no human or animal was harmed during collecting data. And this research work has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

Availability of Data and Materials

All data have been collected from Google Scholar and Scopus. Moreover, there is no individual person's data in any form (including individual details, images or videos) in this study.

Competing Interests

There is no financial competing interest in this research.

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