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LEATHER WASTE TO ENERGY: ENVIRONMENTAL BENEFITS. A REVIEW

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Abstract. This review outlines the main approaches to developing the energy recovery processes from leather waste. It discusses the challenges and opportunities for accelerating the utilization of solid leather waste for biofuel production and considers promising methods for processing biomass, chromium waste, sewage sludge, and fat into bioenergy feedstocks.

Keywords: leather solid waste, tannery sludge, grease waste, energy recovery, biofuel production.

1. Introduction

The decline in fossil fuel reserves and rising costs, global warming, raw material prices, government policies, consumer awareness, and further technological development are only some of the factors that significantly impact the development of industrial biochemical technology.

Unfortunately, the war in Ukraine significantly exacerbates the energy crisis. Therefore, the use of alternative energy is crucial.

Fossil oil products dominate as fuel for many purposes, especially transport. On the market, alternatives include ethanol, biodiesel, and biogas.[1] Fuel cells are now a viable technology that can readily be put into production, and many funds are being spent throughout the world for this technology development. An example can be new organic fuel cells produced from industrial waste.

Every year, tanneries around the world generate large amounts of solid and liquid waste, most of which is routinely disposed of in landfills.[2] Suppose biomass has not been pre-treated with aggressive chemicals (*e.g.*, waste hides after canning, soaking). In that case, it is widely used as a valuable by-product in the production of animal feed, fertilizers, cosmetics, *etc.*[3] The recycling of shank and tanned leather waste and the effective disposal of leather waste remain big issues. Today, tannery waste-to-energy methods are promising, cost-effective, and technologically feasible.

Thermal processes, such as incineration, pyrolysis, and gasification, are used for energy recovery. Thermal methods seem to be the easiest option since it enables energy production along with the elimination of leather waste. Unfortunately, these processes need particular attention due to possible environmental issues, such as the emission of the toxic hexavalent chromium, and the generation of halogenated organic compounds and poly-aromatic hydrocarbons. Moreover, this approach is less favorable from an environmental point of view (increase of greenhouse gas emissions) and does not exploit all the positive mechanical characteristics of leather. Since leather waste contains more than twice as much energy as coal, its conversion into energy is used in tanneries for the processing of hides and skins.

Modern methods of sustainable resource recovery from solid biowaste and wastewater using microbial energy generation systems were comprehensively analyzed in the literature.[2,4-6] They are effective both for nutrient recovery, heavy metal removal, and biofuels production. Organic sorbents are often used to intensify anaerobic digestion.[7-9] Anaerobic digestion of biomass is used not only for electricity and heat production but also for nutrients and organic matter reuse in agriculture effectively closing the cycle, which is a basic principle of sustainable development technologies.[10,11]

Biogas and biodiesel production from biomass and fat waste has become widespread in many countries. Thus, it is possible to implement a closed cycle of energy production/waste recycling in the leather industry.

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2. Aim and Structure of the Review

This review focuses on leather waste used for energy production and waste conversion to bioenergy. The purpose of this review is to highlight all the latest research achievements in the field of leather waste recycling.

Recycling of leather waste involves the use of macromolecular constituents of leather and other organic feedstocks, with the ultimate goal of offering practical implications for the industry in terms of sustainability and identifying research gaps that can help future authors and companies in their work.

The third section of this review describes the challenges associated with leather disposal and reports on the environmental impact of leather waste.

The fourth section presents the chemistry of waste methanization. The chemical conversion of waste into biodiesel and ethanol is also discussed.

The fifth section analyzes and discusses the main options for leather waste use for biogas production.

Section 6 discusses the conversion of waste fats and other waste from the tanning industry into biodiesel and bioethanol.

The conclusion discusses practical implications for business and academia to highlight the gaps in the work presented and suggests new research directions in terms of industrial exploitation of bioenergy resources.

The literature analysis was conducted using Scopus, Google Scholar, and Web of Science databases. The keywords used correspond to those listed at the beginning of this article. The topics and subtopics of the papers analyzed for this review are listed in Table 1.

It has been found that the chemical properties of the waste and its ability to biodegrade are fundamental to the efficient industrial conversion of leather waste into energy.

However, modern approaches are usually quite far from full industrial application. There are still some gaps in the scientific literature on the conversion of bio-waste into energy products.

Table 1. Number of papers on topics and subtopics in this review

Topic		Subtopic	Number of papers
3	Leather waste and leather waste recycling for energy	Classification of leather waste	12
		Potential for processing organic waste into biogas	5
4	Chemical transformations of waste to biogas and biodiesel	The chemical transformations of waste to biogas	8
		The chemical transformations of waste to biodiesel	4
5	Conversion of leather waste to biogas	Conversion of leather solid waste	14
		Processing of tannery sludge	4
6	Conversion of leather waste to biodiesel	Grease waste residue to biodiesel	6
		Biochemical conversion of tannery sludge	5

3. Leather Waste and Leather Waste Recycling to Energy

Leather manufacturing is one of the most ancient and widespread industrial activities.[12,13] The material (leather) mainly composed of a natural macromolecule (collagen) is chemically modified to obtain durable goods. The global leather industry produces about 1.7 billion m^2 of leather, with an estimated market value of about 34 billion euro.[14-16]

Leather tanning is the process of converting raw hides or skins into leather. The objective of the tanning process is to treat the hides and skins in such a way that the material is prevented from decaying, resistant to wetting, is supple and durable. During the tanning operation, collagen (the main protein of the skin) is fixed to reactive parts of the tanning agent, thus stopping the biological decaying of the material.[17,18] There are many variable products capable of being fixed to skin to achieve tanning.[15]

The manufacturing process for leather preparation can be divided into three basic sub-processes: the preparatory house stage, the tanning stage and the crusting stage.[19] Surface coating can be an additional step in leather processing.

Leather production uses high amounts of chemical agents and water and, therefore, is often associated with the production of high amounts of solid waste, and high organic loads in the wastewater. It is described that in one metric ton of rawhide tanned, only 20% is transformed into leather (Fig. 1).[13]

Fig. 1. Distribution of leather wastes

Solid waste includes salt from raw hides/skin dusting; raw leather/leather scraps; hair from the calcification/depilation process, which may contain lime and sulfides; and meat from raw hides. Other waste includes shavings containing chromium (III) oxide; wet-blue trim containing chromium oxide (Cr_2O_3), syntans, and dye; and polishing dust, which also contains chromium oxide, syntans, and dye.[20]

The solid waste is categorized as fleshing waste (50–60%), chrome splits, chrome shaving, buffing dust (35–40%), skin trimmings (5–7%), grease waste, and hair (2–5%).[20-22]

Untanned solid waste (***mainly biomass)*** is a renewable resource providing bioeconomy development. Sustainable supply, extensive availability, easy accessibility, and production potential characterize renewable biomass as a unique material source for the production of bioenergy, bio-fuels, and bioproducts.[23]

Nowadays, attention has been given to the conversion of biomass to bioenergy and biomaterial due to the significant benefits they offer in many aspects. The strategy of biorefining has been recognized as the main element to boost the emerging bioeconomy by offering a wide range of products from a wide range of biomass sources to satisfy the diverse community demands. The leather industry generates plenty of proteinase biomass.

During chrome tanning, large amounts of ***chromium-containing leather waste*** are generated. The main compounds are trivalent chromium and collagen.[22,24] Indirect recycling of such waste to biofuels involves two approaches: a) extraction of collagen[25] or gelatin from chromium-containing leathers and b) use of the waste after dechroming treatment.[26]

It is common to pre-treat leather waste before anaerobic digestion.[27] Table 2 presents various pretreatments to increase biogas production.[28]

Table 2. Pretreatment for biogas production from leather waste

Pretreatment	References	Method conditions	Result
Thermal	19, 22, 28	150°C	Improves digestion to a small extent
Ozonation	16, 22	0.18g O_3/g w.	Biogas production increase
Hydrodynamic cavitation	22,23	5 bar/120 min	Biogas production increase
Enzymatic (*lipase*)	27,31	0.75g	Biogas production increase
Enzymatic (*S.cerevisiae*)	27,31	1g	Improves digestion by increasing biogas production
Chemical (K_2HPO_4)	16, 22	22.94 g	Biogas production increase

Wastewater from tanneries is one of the most polluting among industrial waste. It is divided into the following types: vegetable tanning not containing chromium (used to produce heavy leathers such as shoe soles, bags, belts, and straps) and chrome tanning containing chromium (used to produce light leathers).[22,23]

Cr (III) and other inorganic substances are removed if their content in the waste is significant. Otherwise, such waste is unsuitable for biochemical treatment. Existing chromium recovery technologies (along with removal efficiencies) are presented in Table 3.[26]

According to some research,[19,27,28] if the biodegradable fraction of the waste is less than 60%, it is more efficient to use thermal waste treatment methods.

Wastewater from tanneries is treated to produce nutrients using traditional biological methods (in aeration tanks), but nitrogen compounds are slightly removed. They are promising for the conversion to biogas, but the main problems of their effective methanization include high nitrogen content and the presence of non-biodegradable substances (Cr, Al compounds, *etc*.).

Researchers actively study the conversion of harmful **tannery sludge** to alternative renewable energy sources.[17] Anaerobic digestion is a widespread biological treatment process using anaerobic microorganisms to produce biogas from tannery sludge. The biological conversion of catalytic action for the production of biodiesel and hydrogen from wastewater sludge has been paid relatively little attention today.[25,27]

Grease waste can be used to produce biodiesel and biogas by anaerobic digestion.[19] The composition of fatty acids in the leather waste was found to be higher compared to vegetable oil. However, the sustainable production and storage of this promising energy carrier is still a challenge.[29,30]

On average, animal fats contain 5-30% fatty acids, which lead to soap formation and make their separation difficult. The authors studied the composition of fatty acids present in fat from tannery waste (Table 4) and verified that it contains a higher amount of fatty acids compared to vegetable oil.[22,25]

Experimental results have shown that tannery wastes and their mixtures can be converted into a promising fuel with relatively high calorific value.[19,28] Thus, the results of Table 5 show that animal wastes give a higher yield of biogas with high methane content than common vegetable raw materials. Thus, leather waste, which is unsuitable for direct processing and hydrolysis, can be a potential feedstock for biofuel production.

Table 3. Existing Cr recovery technologies

Process	Removal efficiency
Thermal treatment under temperature ranges of 100–1000 ◦C with an interval of 100 ◦C for 4 h	98.00 %
Enrichment method	43.49 %
Bioleaching process	92.50 %
Magnetic flocculation	99.12 %
Indigenous sulfur-oxidizing bacteria-based bioleaching	98.00 %
Alkalifying-oxidizing method-based acid leaching	92.60 %
Quillaja bark saponin as biosurfactant and H_2O_2-based oxidative treatment	70.00 %
Oxidation method	70.00 %
Ultrasound-assisted SCWO	99.60 %
Hydrometallurgical processes and acid solution	97.00 %
Acidithiobacillus ferrooxidans based bioleaching	91.20 %
Electrokinetic process	80.01 %
Three-stages processes: extraction of Cr from waste, oxidation of Cr(III) to Cr(VI), and reduction of Cr(III)	83.00 %
Reduction–chlorination–volatility	98.39 %

Table 4. Main fatty acids present in the fat extracted from tannery wastes

Type of Fatty Acid	Carbon Chain	%
Miristic Acid	C14	4.18
Palmitic Acid	C16	24.22
Steric Acid	C18	30.23
Oleic acid	C18	37.76
Linoleic acid	C18	2.78
Linolenic Acid	C18	0.17
Araquic Acid	C20	0.20
Undetectable	-	0.46

Table 5. Organic waste recycling potential[22,25,27]

Types of waste	Biogas yield, m^3/t	CH_4 content, %
Collagen-containing wastes	200-400	58-62
Fat and fat residue	250-1200	60-72
Tannery sludge	260-490	68-74
Beet pulp	50-160	58-62
Beer grit	150-200	60-64

4. The Chemical Conversion of Waste to Biogas and Biodiesel

Depletion of oil reserves, fuel costs increase, and severe environmental deterioration are critical challenges the world is facing. These concerns have incentivized the use of renewable biomass-derived biofuels such as bioethanol, biogas, and biodiesel. Bioethanol, mainly derived from sugarcane (Brazil) and corn (USA), was introduced in the 1970s as an additive or complete replacement for petroleum-derived car fuels.[31]

Anaerobic digestion is the most well-known method for biogas production, whereby carbon dioxide (CO_2) and methane are fully recovered in the absence of oxygen.

The digestion process includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each stage is a function of the metabolic condition of various microorganisms.

The anaerobic decomposition of organic matter is a three-stage process, dependent on the physiological group of bacteria involved.[32]

In the first stage, the heterogeneous group of anaerobic bacteria initiates enzymatic hydrolysis of the complex multi-carbon substances like proteins, lipids, and polysaccharides. In this case, along with the bacteria enabling the polymer hydrolysis, there are micro-organisms able to decompose the monosaccharides, organic acids and alcohols. The microorganism activity contributes to the generation of hydrogen, carbon dioxide, low-molecular-weight fatty acids, alcohols, and some other compounds. At this stage, the obligate anaerobes get involved.[23] The reactions are listed in the equations as follows (1–3):

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow C_6H_{12}O_6 \quad (1)$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (2)$$

$$RCH\ NH_2\ COOH \rightarrow^{(O)} RCOCOOH + NH_3 \quad (3)$$

In the second stage, the acetogenic bacteria transform hydrogen, carbon dioxide, other one-carbon compounds, and some more complex substances into low molecular organic acids through the intermediary formation of acetyl CoA.[27,28] The microbiology of this stage has not been thoroughly studied yet.[33-35] The second stage is most often described by the following Equations (4–6):

$$CH_3CH\ OH\ COOH + 2H_2O \rightarrow$$
$$\rightarrow CH_3COOH + CO_2 + 2H_2 \quad (4)$$

$$RCH_2COOH + 2H_2O \rightarrow 2RCOOH + 3H_2 \quad (5)$$

$$C_2H_5OH + H_2O \rightarrow^{(o)} CH_3COOH + 2H_2 \quad (6)$$

The decomposition of organic matter in the final stage is done by microorganisms. The microorganisms use the metabolites generated in the earlier stages. CH_4 and CO_2, as well as a small amount of H_2S, are generated in the final stage of anaerobic decomposition of organic matter in ecosystems with low sulfate content.[36]

A mixture of hydrogen and carbon dioxide is usually the source of carbon and energy for methanogens. Formiate is another potential source of carbon and energy supplied to methanogens. Acetate is more important for methanogenesis. According to some research, the rate of CH_4 production from acetate in the biological reactor is 72%.[32,36] The above can be described by the following reactions (7–9):

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (7)$$

$$4HCOOH \rightarrow CH_4 + 2CO_2 + 2H_2O \quad (8)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (9)$$

The parameters like pH, TS, VC, COD, and total N directly influence the burning yield of biogas. Although pH 7.8 is outside the appropriate range of leather waste and trimmings in the mixtures to be biodegraded, such pH values were closer to the anaerobic digestion (AD) range. It proves that it is not the pH value of the residues that is the limiting factor.[37]

The feedstock for biodiesel production is methanol and vegetable oils or fats (alkaline or acid catalyst is used) (Fig. 2).[37] The transesterification reaction (alcoholization) generates methyl esters of higher fatty acids.[38]

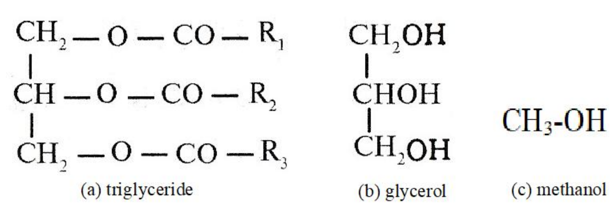
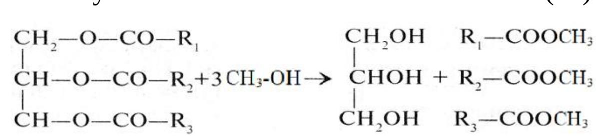


Fig. 2. The feedstock for biodiesel production

The reaction of 3 fatty acids with methanol in the presence of a homogeneous alkaline catalyst (up to a maximum of 1 mg KOH/g) requires raw materials with a low fatty acid content as shown in the literature (10):[29]


(10)

Animal fats usually contain 5–30% of fatty acids, which leads to soap generation and makes separation difficult. To fix it, a pre-treatment (11) can be done by the esterification of methanol with sulfuric acid as a catalyst, then fat can be transesterified by the conventional process to obtain methyl esters. There are two main stages in the pre-treatment process: refining and removal of fatty acids (deacidification). In refining, it is possible to reduce the content of water, ash, acids, or even nitrogen. Deacidification is a physical extraction process, where methanol is usually used (R_1: $-CH_3$).

$$R - COOH + R_1 - OH \rightarrow R - COOR_1 + H_2O \quad (11)$$

The use of ethanol instead of methanol in transesterification reactions has many environmental benefits.[38]

Bioethanol can be used for the alcoholization reaction. Efficient conversion of feedstocks to bioethanol requires innovative and sustainable approaches to minimize environmental impact.[39] Such conversions occur via the reactions (2) and (12):

$$CH_3CH\ OH\ COOH \rightarrow CH_3CH_2OH + CO_2 \quad (12)$$

The use of ethyl esters of long-chain fatty acids from oils as a biodiesel has several advantages compared to the use of methyl esters. For example, biodiesel fuel was prepared by transesterification of rapeseed oil with absolute ethanol (99.9%), which was dehydrated with freshly prepared calcium oxide (95%) using sodium ethoxide as a catalyst. The yield of biodiesel from rapeseed oil increases from 85-90% to 95-98% without the waste fraction of glycerin (10-15%).[40]

5. Conversion of Leather Waste to Biogas

Aerobic stabilization of leather waste and tanning sludge reduces waste and emissions, which is important for sustainable waste disposal.[41] Organic waste originating from leather production (such as biomass and flesh) can be used to produce biogas by anaerobic digestion. Anaerobic digestion of leather waste is the most known method for biogas production with a complete recovery of carbon dioxide (CO_2) and methane (CH_4) in the absence of oxygen.[41,42]

It is not allowed to dispose of leather waste in landfills. This is considered an unsafe practice due to the high organic content and the presence of trivalent chromium. Under these considerations, anaerobic digestion is a viable alternative for recycling the waste containing chromium (III).[24,42,43]

Leather waste should be mixed with other residues in co-digestion due to high nitrogen content and to ensure a proper C:N ratio of 20–30:1.[44] Additional digestion reduces undesirable contaminants (including Cr^{+3}, Cr^{+6}). Co-digestion of wood shavings and tannery sludge can reduce electricity consumption by more than 70%.[45] In the case of hide waste, rinsing is required before the digesters due to the presence of sulfides that can increase hydrogen sulfide concentration in the biogas.[46]

The researchers have studied the anaerobic digestion of chromium-containing solid waste from tanneries, and thermophilic anaerobic digestion of tannery shavings and sewage sludge.[47] The pH value is neutralized due to the process in both sludge and shavings starting at an average of 7.6 and increasing to 8.2.[48] According to other research,[49] a high concentration of organic salt indicates a high organic load of cattle skin waste, which makes them suitable for anaerobic digestion.

Kameswari *et al.*[50,51] utilized ozonation as an alternative to enhance the chemical demand for soluble oxygen, given that sludge hydrolysis necessitates a longer retention time. The use of ozone for cellular solubilization and hydrolysis of the sewage sludge breaks down the cell wall and releases COD, thereby increasing biogas production. The infusion of 0.18 g of O_3 per 1 g of total solids has resulted in a substantial increase in biogas production (up to 310 mL/g). In their another study,[52] the use of enzymes as a pre-treatment did not result in a significant change in biogas production, with an increase from 379 to 389 mL/g. Due to the high cost of enzymatic treatment, there is no reason for its widespread use.

Many researchers have studied the impact of certain compounds present in tannery wastewater on biogas production. Wastewater and sewage sludge contain NaCl, Na_2CO_3, antiseptics, and antibiotics. These compounds are inhibitors of the fermentation process with methane generation. Adding Na_2CO_3 reduces methane generation from 220 to 38 mL/g. In the presence of NaCl, methane generation was 594 mL/g, while it reached 113 mL/g without sodium chloride. High concentrations of tetracycline and norfloxacin antibiotics (25−100 mL/g) have resulted in a significant decrease in biogas production. Therefore, antibiotics inhibit the microorganism's association from the very beginning of the fermentation.[53,54]

Various studies have investigated the co-digestion effectiveness for biogas production. For example, the efficiency of biogas production from the co-digestion of municipal waste and cow dung was investigated.[55] It was found that the best results were achieved at a weight ratio of 70:30 % (cow manure to tannery sludge) under mesophilic temperature conditions.[26]

Agustini *et al.*[55] have studied the biogas production capacity by varying the feedstock to ascertain the optimal conditions for biogas production. Tannery sludge and shavings were used in conjunction with three additional biomasses to evaluate the efficiency: microalgae biomass, cattle hair, and commercial silicone. The results demonstrated the co-digestion of tannery sludge and shavings with microalgae enhances biogas production efficiency. In this case, the biogas production rate was increased by 43.3 mL/g, along with an increasing C/N ratio.[49,56]

The data obtained indicate the main substances of the tannery sludge decreasing the efficiency of the biogas production from wastewater: hydrocarbonates, sulfates and chlorides[57]. The co-digestion of sewage sludge and other tannery waste can be an excellent resource for biogas production. They can be used directly in tanneries as a heat source or for electricity generation.[55,57]

6. Conversion of Leather Waste to Biodiesel

Biodiesel is produced by transesterification of triglycerides or free fatty acids with short-chain alcohols. Feedstock for biodiesel production includes vegetable oils and animal fats such as soybean oil, rapeseed oil, palm oil, and waste cooking oil.[10,57] Recently, the focus has been on the processing of fatty waste from the food and leather industries.[57]

Transesterification as a method of fatty waste processing can be classified as catalytic and non-catalytic. In catalytic transesterification, basic or acidic catalysts are usually used, with basic catalysts being the most common. In non-catalytic transesterification, enzymes are used, but this process has high production costs and difficulties with the separation and reuse of enzymes.[57,58]

The tanning industry generates a large amount of waste, including animal fat as the most important waste with a high calorific value. This waste has a high protein content, which makes it possible to use an anaerobic digester to process it. However, many researchers have doubts that this resource is economically viable for utilization in biodiesel and bioethanol production.

There are two main stages in the pre-treatment of fatty waste: refining and removal of fatty acids (deacidification). At the refining stage, it is possible to reduce the content of water, ash, acids, or nitrogen. During the deacidification, a physical extraction process takes place, usually using methanol.[49,59-60]

The authors[61] have analyzed the pretreatment of fat using alkaline methanol solutions (methylammonium tetrahydroxide) instead of pure methanol and obtained a 98.4% reduction in fatty acid content. Then, it proceeded to transesterification and production of biodiesel fuel. That meets the majority of the requirements set out in the European standard EN 14214 of 2012.

The scientists[62] examined the viability of biodiesel production (for injection engines) from leather waste. To assess the performance, a comparison with conventional diesel fuel was done. Analyses revealed comparable emissions and performance characteristics. This alternative is promising for several reasons, including its higher cetane number, which provides better combustion. The density and viscosity have a great influence on the circulation, injection, and preservation of fuel in the engines. However, both diesel and biodiesel are very similar in density.

The use of leather waste as an alternative resource for biodiesel production is very promising when certain fundamental parameters are analyzed and adapted to current regulatory requirements. Booramurthy *et al.*[63] have verified that the sulfate ash and carbon residue content comply with the European, UK, and USA standards.

The biological conversion of tannery sludge for biodiesel production has been paid relatively little attention.[25,63] For example, an innovative process of biodiesel production from wastewater using photocatalytic action has been developed.[64] The fat-rich sludge from pork tanning operations and a new photocatalyst called «CdS» were used to convert the fats.

In the recent study by Kumar and Thakur,[64] the extraction of lipids from a secondary tannery sludge using in situ transesterification was applied. The authors have confirmed that the chloroform-methanol method yielded a higher lipid content (22.8%) with a lipid extraction efficiency of 98.5%. Based on these findings, biodiesel from secondary tannery sludge could be considered a promising energy option with a techno-economic feasibility.[25,65,66]

Therefore, leather waste can be considered an inexpensive and promising raw material for biofuel production, which can reduce the cost of biogas and biodiesel production on the global market and make it more profitable for the industry.[66,67]

The main advantages of producing biofuels from leather waste are as follows:[24,25,67]

- Feasible, economical, and well-established process for tannery waste management using the co-digestion technique
- Digestate residue can be used as nutrients in agricultural fields
- Easy to operate compared to a thermal treatment plant and not necessarily require highly skilled technical personnel
- Reliable and well-established technologies of biogas and biodiesel generation and leather waste reduction.
- Easy and flexible compared to the thermal process.

7. Conclusions

There is a need to implement sustainable practices at all stages of the leather waste management and green technologies development, and innovative bioremediation techniques in regional leather industries.

Due to the large waste amount, there is a space limitation for waste disposal. The disposal cost incurs extra expenses to the industries. Therefore, to sustain the leather production process, there must be a mechanism for leather waste conversion to high-value materials that can be used for different applications.

In this review, we have outlined the main trends in energy recovery from leather waste, including chemical transformations, bioengineering, modeling tools, and downstream biochemical process engineering, as well as many case studies. Ultimately, the success of industrial biochemical technologies depends on the economic efficiency of specific processes.

We also offer practical implications for the leather industry in terms of sustainability and identify research gaps that future authors and companies can address in their work.

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ШКІРЯНІ ВІДХОДИ В ЕНЕРГІЮ: ЕКОЛОГІЧНІ ПЕРЕВАГИ. ОГЛЯД

Анотація. *У цьому огляді ми окреслили основні підходи до розробки процесів вилучення енергії зі шкіряних відходів. Обговорено виклики та можливості для прискорення утилізації твердих шкіряних відходів для виробництва біопалива. Розглянуто перспективні методи переробки біомаси, хромових відходів, осадів стічних вод і жирів на біоенергетичну сировину.*

Ключові слова: *тверді відходи шкіряного виробництва, шлами шкіряних заводів, жирові відходи, рекуперація енергії, виробництво біопалива.*