


Treatment and utilization of chromium-tanned leather waste for energy materials as an alternative approach to current energy technologies: a review

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ABSTRACT

The textile and footwear industries generate over 1.2 million tons of chromium-tanned leather waste annually, posing severe environmental and health risks due to the presence of toxic Cr(III) and Cr(VI) compounds. This review critically evaluates current treatment technologies and valorization strategies for repurposing this waste into high-performance energy materials. Although leather waste contains up to 50–60 % organic content and 3–5 % chromium, its potential as a carbon-rich precursor remains underexplored. This review is the first to comprehensively address its application in energy systems, with a focus on electrochemical performance, specific surface area (ranging from 300 to 1200 m²/g in modified carbonized materials), and environmental impact mitigation. Promising approaches include hybridization with carbonized biomass, metal oxides, and conductive polymers, resulting in materials suitable for supercapacitors, batteries, fuel, and solar cells. Life-cycle assessment (LCA) studies show up to 30 % reduction in environmental footprint compared to conventional synthetic materials. Despite these advances, challenges remain in scaling laboratory successes to industrial production. The review concludes that while significant strides have been made, further research is needed to optimize material properties, improve process economics, and fully integrate LCA into development pipelines to support sustainable, large-scale implementation of leather waste-derived energy materials.

1. Introduction

The leather industry is one of the oldest and most globally established industrial sectors, with a current market value estimated at USD 407.37 billion in 2024. This market is projected to grow at a compound annual growth rate (CAGR) of 7.40 %, reaching approximately USD 541.69 billion by 2028 [1]. Globally, leather production exceeds 23 billion square feet annually, with the footwear industry accounting for over 65 % of this output, while the remaining 35 % is directed toward apparel, furniture, and accessories. Major leather-producing countries include China, India, Hong Kong, Italy, Turkey, and France [2,3]. Although this sector contributes significantly to economic development and employment, it also generates a substantial volume of waste and environmental pollutants, raising critical sustainability concerns.

A major source of environmental burden in leather manufacturing is chromium-tanned leather waste, which constitutes over 80–90 % of all tanned leather globally due to the superior durability and flexibility provided by Cr(III) salts [4,5]. However, this tanning method produces significant amounts of hazardous solid waste, estimated at 600,000 to 800,000 tons annually worldwide, comprising scraps, shavings, and trimmings, often containing 2–5 % residual chromium [3,6]. Improper disposal or incineration of this waste can lead to the formation of toxic hexavalent chromium (Cr(VI)), posing serious risks to human health and ecosystems [7,8]. Furthermore, chromium-leather waste is largely non-biodegradable and classified as hazardous under various international regulations, making its treatment and disposal both technically and economically challenging [9].

Traditionally, chromium-tanned leather waste has been landfilled or

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incinerated, but both methods are unsustainable due to land scarcity, long degradation periods, and emission of toxic gases [10]. Alternative valorization routes, such as the recovery of collagen fibers, gelatin extraction, or use as a filler in composites, have shown promise but remain limited in scale and scope [11]. Given the high carbon content, thermal stability, and dense macromolecular structure of leather, there is a growing interest in repurposing chromium-tanned leather waste as a precursor for value-added materials, particularly in energy-related applications [12,13]. Recent studies have explored the incorporation of leather waste into polymer-based composites and hybrid materials, particularly for reinforcement purposes [14–16]. However, the potential of chromium-tanned leather waste as a carbon-rich feedstock for advanced energy storage materials, such as electrodes for batteries and supercapacitors, has not been systematically reviewed. Most existing literature focuses on conventional applications and fails to address the electrochemical performance, material design strategies, and lifecycle considerations critical for scaling up such solutions (Scheme 1).

This review aims to bridge that gap by providing a comprehensive overview of current treatment methods, material properties, and energy-related applications of chromium-tanned leather waste. Special emphasis is placed on the electrochemical characteristics of derived materials, including surface area, conductivity, and specific capacitance, with a view toward practical deployment in sustainable energy systems. The novelty of this work lies in its focus on cutting-edge strategies for transforming chromium-tanned leather waste into functional energy materials, integrating environmental impact assessments, and discussing pathways for industrial scalability. By identifying recent advances and key research gaps, this review supports the advancement of sustainable technologies that not only mitigate environmental pollution from leather waste but also contribute to the development of next-generation, biobased energy devices.

2. Environmental issues related to raw leather waste

The leather business, while commercially important, is associated with considerable environmental issues due to the production of hazardous substances during the tanning process. These wastes are often categorized into three types: solid waste, liquid effluents, and gaseous

emissions, any of which may lead to environmental harm if improperly handled.

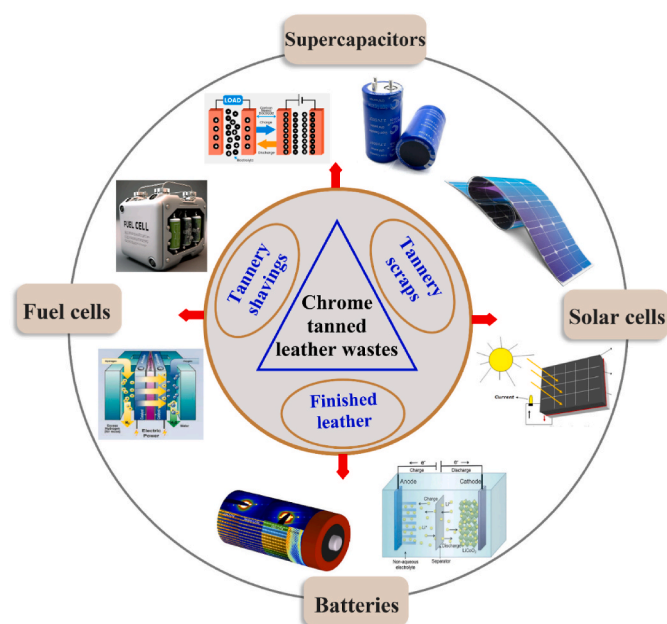
2.1. Liquid waste

Leather production involves three fundamental stages: preparation, tanning, and crusting, each of which generates various types of waste, including solid waste, wastewater, volatile organic compounds (VOCs), and toxic chemicals [5]. The leather industry is recognized as one of the most environmentally impactful sectors, with significant economic and ecological implications.

Among the production stages, pre-tanning and tanning processes are the primary sources of pollution, accounting for over 80 % of the total contaminants released by the industry. These processes generate large volumes of wastewater containing high concentrations of hazardous chemicals. Notably, the tanning stage significantly alters the pH of the wastewater, leading to increased levels of chemical oxygen demand (COD), sulfates, and total dissolved solids (TDS) [20]. Dehairing, which is part of the pre-tanning stage, involves the removal of hair from hides using specific chemical agents. As illustrated in Fig. 1, this step plays a major role in wastewater pollution, contributing approximately 84 % of the biological oxygen demand (BOD), 75 % of the COD, and 92 % of the suspended solids (SS) present in tannery effluent. Sodium sulfide, commonly employed during dehairing, is particularly detrimental to wastewater treatment systems and poses significant environmental risks [15,21–24].

2.2. Solid waste

The production of leather materials generates large quantities of solid waste, primarily composed of proteins, lipids, and significant amounts of chromium. Proper management and safe disposal of this waste are crucial, as inadequate handling can result in severe environmental and public health hazards, as illustrated in Fig. 2. In addition, post-tanning processes contribute substantial quantities of heavy metals to water bodies, leading to ecological imbalances and increased salinity in rivers and other aquatic systems. These changes disrupt ecosystems across various trophic levels, from microorganisms to humans. One widely used method in leather processing is chromium tanning, which plays a vital role in transforming raw animal hides into durable and functional leather products. This technique has attracted considerable research interest due to its efficiency and effectiveness [25]. In this process, trivalent chromium sulfate salt $[\text{Cr}(\text{OH})\text{SO}_4]$ is commonly used



Scheme 1. Different energy technology applications of chromium-based leather waste energy materials. Reproduced with permission from Refs. [17–19].

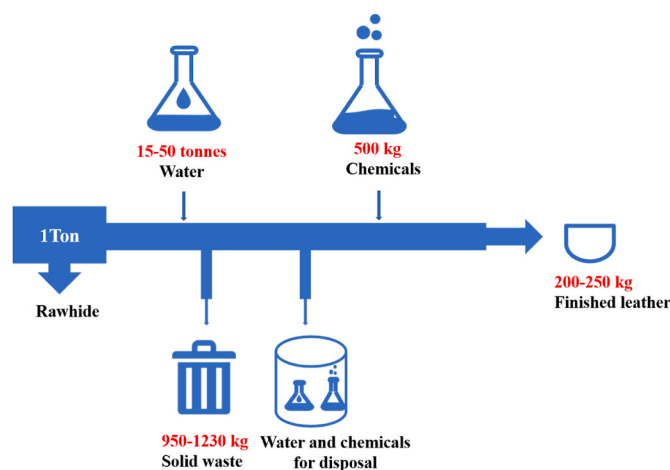


Fig. 1. Generated wastes from raw leather source (adapted with the permission of 40 European Commission Reference Reports - JRC, Best Available Techniques (BAT) Reference Document for the Tanning of Hides and Skins, Industrial Emissions Directive 2010/7) [15].

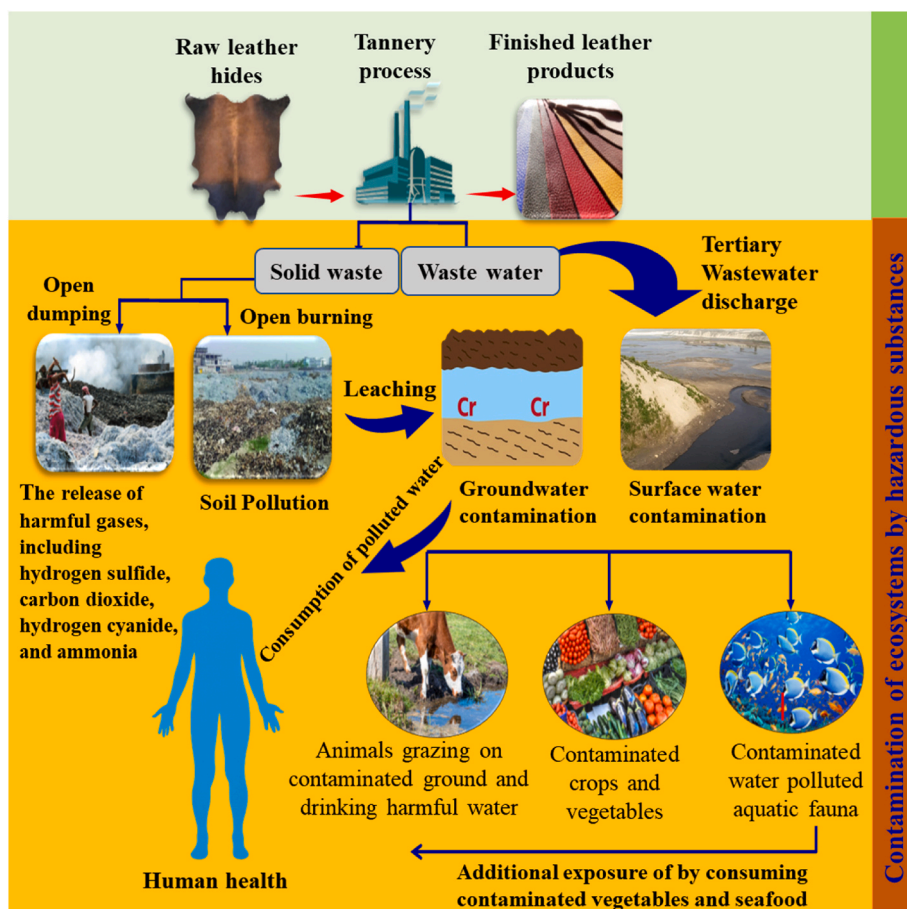


Fig. 2. Effects of tannery discharges on the environment and human health. Reproduced with permission from Ref. [5] and ref. [15].

and is considered one of the most potent tanning agents. Although alternative tanning methods utilizing aldehydes, minerals, oils and vegetable tannins have been developed, they generally offer inferior results compared to chromium-based tanning in terms of performance and durability.

To date, several other tanning methods have been developed, including the use of aldehydes, minerals, oils, and vegetable tannin, but show inferior results as compared to the conventional tanning technique using chromium [26]. Amongst the different advantages, this technique is both cost-effective and rapid. However, pollution generated by chromium solid waste products makes this tanning process particularly detrimental to the environment and human health. During the tanning process, the majority of the metallic salts used are often discharged into surrounding water, while the leather absorbs around 60–80 % of the chromium applied. According to the literature, chromium exists in various oxidation states, with the +3 and +6 states being the most common. Of particular biological concern is chromium due to its dual nature: while trivalent chromium (Cr^{3+}) is an essential element involved in glucose metabolism in humans and other animals [5], hexavalent chromium (Cr^{6+}) is highly toxic and carcinogenic. The use of chromium, especially in its hexavalent form, has been increasing across multiple industries, including tanning, mining, galvanization, electrical applications, metal extraction, coating, and electroplating [21,27]. As such, these industries discharge vast amounts as harmful waste into the environment from tens to thousands of milligrams of this hexavalent chromium ion. This metal ion possesses several serious health effects, such as damage to the nervous system, skin, DNA, and immune system. The rapid conversion of chromium +6 to +3 upon crossing the cell membrane this promotes binding with macromolecules that primarily target sites such as the liver, kidneys, spleen, and bone. In addition, this

chromium metal ion causes permanent eye issues if in direct contact [20, 21].

2.3. Gaseous emissions

Tannery plants emit a variety of pollutants during leather processing, including ammonia, hydrogen sulfide, volatile hydrocarbons, and aldehydes, which are released into the atmosphere. These hazardous compounds are generated at different stages of leather production, such as dehairing, liming, and drying. VOCs, such as toluene and benzene, are primarily released during the drying stage due to evaporation. Hydrogen sulfide and ammonia are predominantly emitted during the liming, dehairing, and bating steps. The release of these gaseous substances poses serious environmental and public health concerns [15]. Fig. 3 illustrates the various types of waste generated throughout the leather processing cycle.

3. Leather waste management methodologies

3.1. Thermal treatment process

3.1.1. Pyrolysis/carbonization process

The leather industry is a key segment of the fashion sector, playing a vital role in the production of various leather goods for a wide range of commercial applications and significantly contributing to economic development. However, alongside its economic benefits, the industry generates substantial amounts of waste, which poses serious risks to both environmental and human health. In response, many countries have enacted regulations to restrict the disposal of leather waste in landfills, aiming to mitigate its environmental impact [30–32]. As a

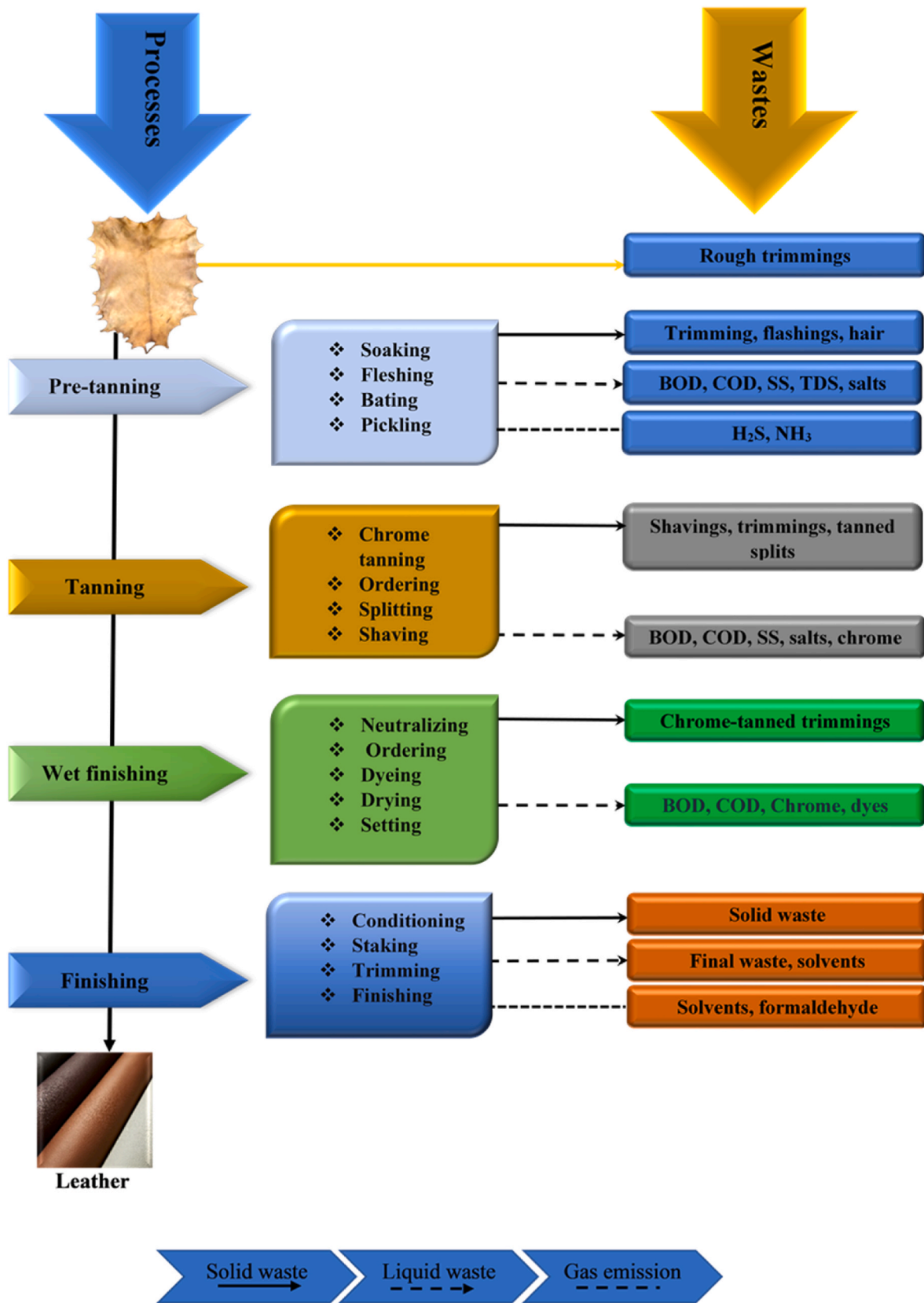


Fig. 3. Illustrating the formation of different waste substances during leather processing. Reproduced with permission from Ref. [28] and ref. [29].

result, various waste treatment technologies have been investigated, among which pyrolysis has emerged as a particularly promising method for managing hazardous solid waste from leather processing. Pyrolysis involves the thermal decomposition of materials in an inert atmosphere, typically using nitrogen or argon, under controlled temperatures. Fig. 4 illustrates the conversion of leather waste into valuable products through this process [33–36].

The conversion of leather waste through pyrolysis to achieve optimal material performance is influenced by several key factors, including particle size, residence time, and processing temperature. Among these, temperature plays a particularly critical role. The typical pre-carbonization stage occurs at temperatures ranging from 400 °C to 500 °C, followed by carbonization at higher temperatures, often between 500 °C and 1000 °C, as shown in Fig. 5. Hydrothermal carbonization (HTC) has emerged as a promising technique for converting solid leather waste into multifunctional biochar. This process introduces oxygen- and nitrogen-containing functional groups into the carbon matrix and operates under relatively moderate conditions, typically between 180 °C and 300 °C [38]. One of the key advantages of HTC is its ability to utilize organic compounds in high-moisture environments, thereby eliminating the need for energy-intensive drying steps. As a result, HTC can reduce energy consumption by 50 % or more compared to conventional thermal processes. Additionally, washing the HTC-produced material can effectively lower the ash content associated with inorganic compounds [39]. Carbonaceous materials derived via HTC have demonstrated applicability across various fields, including renewable solid fuels, soil amendment, carbon sequestration, catalysis, and environmental remediation. Compared to untreated biomass, hydrochar produced from HTC exhibits enhanced energy content, higher aromaticity, and improved combustion properties. Furthermore, the conversion of chromium-tanned leather waste into hydrochar not only addresses the issue of solid waste disposal in the leather industry but also provides a cleaner, renewable energy alternative to fossil fuels [40].

Microwave-assisted pyrolysis is an alternative thermal conversion technique that employs microwave-induced dielectric heating to efficiently process feedstock materials. It is often considered more economically viable and energy-efficient than conventional pyrolysis. In traditional pyrolysis, heat is transferred primarily by convection, from high-temperature gases to the surface of the feedstock particles, and subsequently by conduction toward the particle core [41,42]. However,

due to the inherently low thermal conductivity of most biomass materials, significant temperature gradients often develop between the outer surface and the inner core. Consequently, volatile compounds generated within the core must diffuse outward to hotter regions for further reaction. In addition, conventional pyrolysis typically requires an inert atmosphere and extended processing times. This increases energy consumption and operational costs, thereby limiting its economic feasibility. The size and configuration of the tubular furnace also play a critical role in heat distribution, directly affecting the quality and yield of activated carbon products [43]. In contrast, microwave-assisted pyrolysis delivers energy directly to the biomass via electromagnetic waves, which are absorbed and converted into heat throughout the material. This results in volumetric heating, where the entire particle, including its core, heats uniformly and simultaneously. Dielectric materials, in particular, can attain higher internal temperatures than their surroundings under microwave irradiation, thereby promoting heterogeneous thermal decomposition. Microwave pyrolysis offers several notable advantages over conventional methods, including uniform internal heating, shorter start-up and shut-down times, lower processing temperatures, reduced coke deposition on catalysts, and higher product yields with improved pore development in the resulting carbon materials [44]. Key processing parameters, such as microwave power and irradiation time, significantly influence the characteristics of the final product. For instance, Foo et al. examined the production of activated carbon from durian shells using NaOH activation under microwave heating [45]. At an impregnation ratio of 1.5 and 5-min exposure at 90–180 W, the pore structure and yield showed minimal change. However, increasing the power to 360–600 W substantially enlarged the pore structure, enhancing the formation of both micropores and mesopores, as depicted in Fig. 5.

3.1.2. Gasification

In recent years, the shift toward sustainable energy and the reduction of fossil fuel dependence have become pressing global concerns, as emissions from fossil fuel combustion are major contributors to global warming. The tanning industry, while economically significant, generates large quantities of solid and liquid waste, posing severe environmental challenges. Among the various waste management approaches, thermochemical gasification presents a promising alternative by converting waste into combustible gases that can be utilized for heat and power generation. The efficiency and composition of the resulting syngas are significantly influenced by the type of gasifying agent used, such as oxygen, carbon dioxide, steam, or combinations thereof. In a recent study, Ahmad et al. investigated the effects of using carbon dioxide and steam as gasifying agents for the treatment of leather waste [46]. In this study, the experiments were conducted in a fixed-bed reactor at 900 °C under 2-bar pressure (Fig. 6). The results showed that the process duration was approximately 22 min when using steam, compared to 60 min with carbon dioxide [47]. The choice of gasifying agent is often determined by the desired gas output. For example, Xu et al. investigated the gasification of municipal solid waste (MSW) using three different gasifying agents: steam, air, and hydrogen. The reactor operated under the following conditions: MSW feed rate of 1000 kg/h and a temperature of 1273 K. The flow rate of hydrogen was 45.4 kg/h, while the air flow rate reached up to 890 kg/h. The results showed that the energy input required for hydrogen and steam was nearly identical, whereas it was approximately half for air. This is because, during gasification with air, numerous exothermic combustion reactions occur, releasing significant amounts of energy and thereby reducing the need for external energy input [48]. The composition of the produced syngas varies depending on the gasifying agent used. Different agents result in distinct mole fractions of gaseous products [49,50]. When hydrogen is used as the gasifying agent, the process yields a high concentration of carbon monoxide (CO) and hydrogen (H₂), along with smaller amounts of water vapor (H₂O) and carbon dioxide (CO₂). In contrast, steam gasification produces a higher proportion of H₂ and H₂O, with relatively

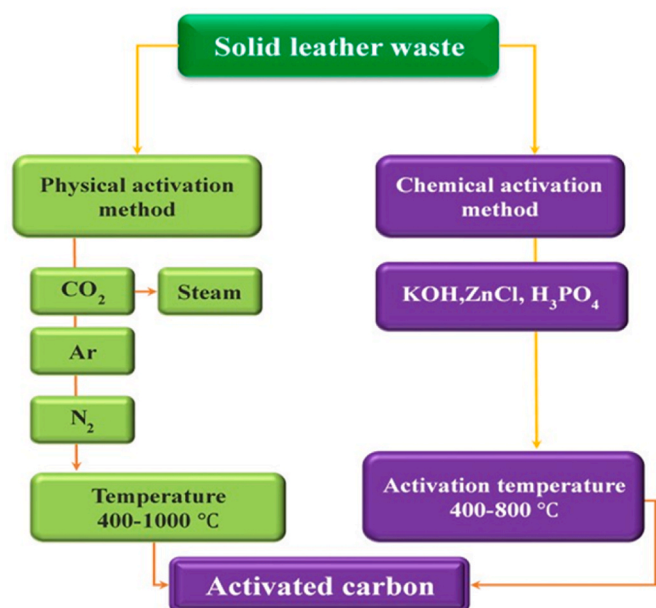


Fig. 4. Process for the activation of solid leather waste for the production of carbonized materials.

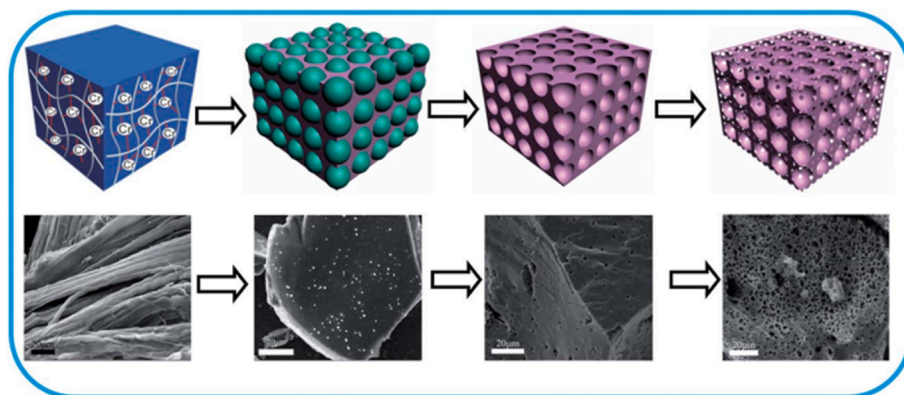


Fig. 5. Schematic representation of prepared porous carbonized chromium-tanned leather waste and its SEM hierarchical porous carbon structure at 20 μm magnification. Adapted with permission from Ref. [37].

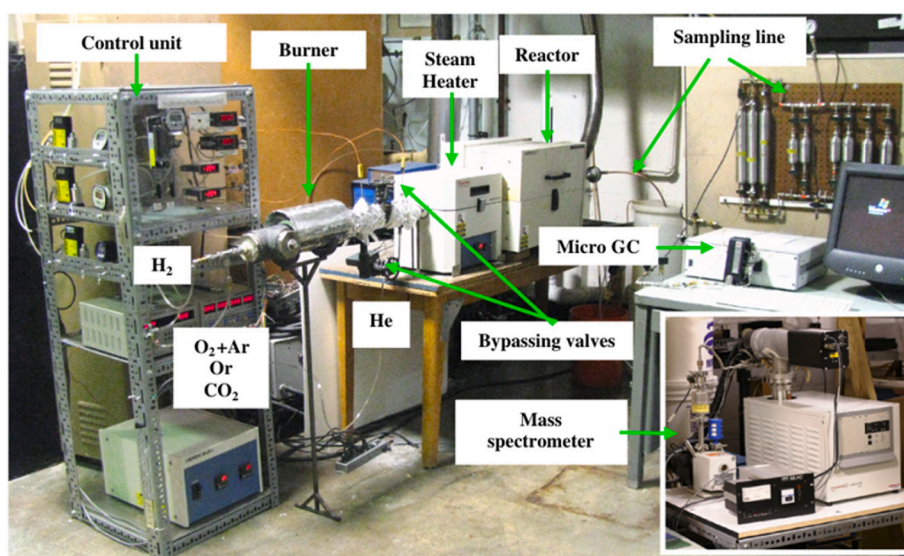


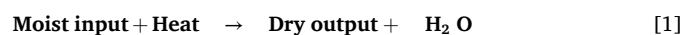
Fig. 6. Instrumental setup image showing wood chips char gasification with steam and carbon dioxide. Adapted with permission from Ref. [47].

lower amounts of CO_2 . These differences highlight how the choice of gasifying agent significantly influences the composition and quality of the syngas produced [51]. Temperature is another critical factor that affects gasification performance. It influences the gas composition, tar content, and reaction kinetics. Pu et al. studied the effect of operating temperature on gas yield and lower heating value during the gasification of pine waste using air, oxygen, and steam in a fixed-bed reactor [52, 53]. Their findings showed that increasing the temperature enhanced hydrogen production. However, as the temperature approached its maximum, the concentration of hydrogen began to decline. This reduction was attributed to endothermic reactions such as the water-gas shift and steam reforming, which shift the reaction equilibrium. Therefore, the hydrogen yield was found to be directly influenced by temperature, increasing up to an optimal point before declining.

Gasification has emerged as a promising and cost-effective method for waste management, particularly in the tanning industry, where hazardous metals such as hexavalent chromium [Cr(VI)] pose significant threats to human health and the environment. Recently, Marek et al. investigated gas production from leather waste using both laboratory- and industrial-scale setups, with the dual aim of evaluating chromium recovery and energy generation [46,54]. In the laboratory-scale analysis, thermogravimetric measurements were conducted over a temperature range of 30 $^{\circ}\text{C}$ –850 $^{\circ}\text{C}$ at a heating rate of 15 $^{\circ}\text{C}/\text{min}$. The results showed an initial mass loss between 0 $^{\circ}\text{C}$ and 100 $^{\circ}\text{C}$, attributed to the

evaporation of moisture entrapped within the leather samples. The most substantial weight loss occurred between 200 $^{\circ}\text{C}$ and 400 $^{\circ}\text{C}$, corresponding to the decomposition of organic matter for the industrial-scale process, 1000 kg/h of leather waste, combined with refuse-derived fuel, was gasified using an air flow rate of 1500–2000 Nm^3/h . The reaction output yielded approximately 360 MJ/h of electrical power and 35 kg of ash containing 50 % chromium. Additionally, the installation of a water condensation system was used to enhance thermal efficiency during gasification. Tannery sludge, a byproduct from the wastewater treatment of leather processing industries, typically contains high concentrations of chromium along with various organic and inorganic hazardous compounds. Through gasification, this sludge can be effectively converted into syngas, a valuable energy source. The gasification process involves four key stages: drying, thermal decomposition (pyrolysis), oxidation, and reduction. The corresponding thermochemical reaction equations for each of these stages are outlined below: [51,55, 56].

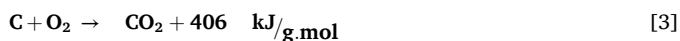
Drying region:



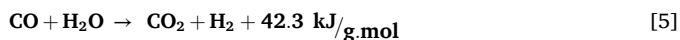
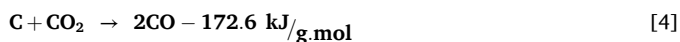
Pyrolysis region:



Oxidation region:



Reduction region:



Zhang et al. investigated the physicochemical behavior of tannery ash during gasification using a custom-built fixed-bed reactor operated at 800 °C. The results revealed high transformation ratios for chromium, zinc, copper, and nickel, which were attributed to the volatile nature of these metals under the experimental conditions [57].

3.1.3. Incineration

Thermal treatment by incineration has proven to be an effective method for the disposal of tannery sludge, making it a widely adopted waste management strategy in the leather industry [58–60]. Tannery sludge typically contains toxic metals, most notably chromium, and the direct landfilling of such hazardous solid waste is prohibited in many countries. Incineration not only reduces the volume of waste by up to 90 % but also enables energy recovery from the process [61,62]. During incineration, oxidation reactions occur, which can lead to the conversion of trivalent chromium (Cr(III)) to hexavalent chromium (Cr(VI)). As Cr(VI) is recognized as one of the most toxic heavy metals, with serious implications for both human health and the environment, it is critical to control the conditions that promote its formation during high-temperature treatment [62,63]. According to the literature, Cr(III) is most susceptible to oxidation at temperatures between 600 °C and 900 °C under incineration conditions [64]. Another important factor influencing Cr(III) oxidation is the presence of alkaline earth metals, which can catalyze the oxidation process. Incineration is typically carried out in a controlled temperature range of 900 °C–1050 °C, conditions that are favorable for Cr(III) oxidation. To inhibit this transformation, acidic compounds such as silicon dioxide (SiO₂) and phosphates can be introduced into the incinerator, which helps shift the reaction environment from basic to acidic, thereby suppressing Cr(VI) formation [59,65,66]. However, due to the high cost of phosphate additives, researchers have been exploring more cost-effective alternatives. Among the potential inhibitors, calcium sulfate (CaSO₄), which forms naturally during the thermal treatment of sludge, has shown promise as an effective suppressor of Cr(III) oxidation. Other compounds, including ammonium sulfamate (NH₃SO₃), ammonium bisulfate (NH₄HSO₄), and sodium bisulfate (NaHSO₄), have also been used to mitigate oxidation during waste incineration processes [67]. Moreover, the rate of Cr(III) oxidation is directly proportional to the incineration temperature up to approximately 900 °C. Beyond this point, in the absence of sulfate-based inhibitors, the oxidation rate begins to decline [68,69]. This highlights the importance of temperature control and the strategic use of additives in minimizing Cr(VI) generation during the incineration of chromium-containing tannery waste.

In general, beyond technical performance and environmental impact, the economic viability of thermal treatment processes plays a crucial role in determining their adoption, particularly in low- and middle-income countries where the leather industry is heavily concentrated. These methods vary significantly in terms of operational costs, energy requirements, and return on investment. Among them, pyrolysis emerges as the most balanced and cost-effective option, offering favorable outcomes in capital investment, energy recovery, and product value, especially when the resulting carbonaceous materials are utilized in high-value applications such as electrochemical energy storage systems.

3.2. Chemical-enzymatic treatment

The majority of waste generated by the leather industry originates

from the use of toxic chemicals during manufacturing, particularly in the pre-tanning and tanning stages, which account for 80–90 % of total pollutants [70,71]. Enzymatic treatment has emerged as a practical solution, reducing reliance on harmful chemicals and improving waste management. Over the past decade, a wide range of enzymes, primarily derived from plants and microorganisms, have been employed in tannery processes to enhance leather quality. These enzymes are favored for their eco-friendly properties, as they minimize chemical, water, and raw material waste [3,72–75]. While both bacterial and fungal enzymes play vital roles in leather processing, fungal enzymes are highly sensitive and rapidly lose activity at temperatures above 60 °C [76,77]. Various enzymes, including proteases, lipases, amylases, chondroitinases, amidases, and phospholipases, are used in leather treatment [77,78]. For example, enzymes in the soaking step accelerate rehydration while reducing harmful chemical use. However, excessive enzyme concentrations can damage collagen, leading to defects in the finished leather.

Dehairing, another critical step, generates 60–70 % of the industry's solid waste. To address this, eco-friendly enzymatic dehairing using keratinase has increasingly replaced the conventional method [79]. Proteases, such as serine carboxyprotease, metal carboxyprotease, and cysteine carboxyproteases, are also widely used due to their diverse amino acid active sites. These enzymes play crucial roles during the treatment process by making the leather material more pliable and softer. In addition, enzymatic unhairing, for example, produces hides with smooth grain surfaces and minimal residual hair, eliminating the need for mechanical stress [74]. However, processing time must be carefully controlled; exceeding 9 h can degrade the hide, particularly in pigskin leather [78].

According to the literature, the use of enzymes in leather processing accelerates production by eliminating certain treatment stages. Studies indicate that enzymatic treatment can reduce chemical COD, BOD, total solids, and sulfide content in effluents by 40–60 % [79]. Compared to conventional chemical methods, enzymatic unhairing reduces sulfide levels in wastewater by approximately 61 %, a significant improvement. The sulfides in the effluent likely originate from disulfide bonds in the enzyme molecules or keratin degradation, which releases sulfur-containing amino acids like cysteine. Beyond environmental benefits, enzymatic processing enhances leather quality [79,80]. Higher enzyme concentrations can more effectively remove non-collagenous compounds, improving key leather properties such as shrinkage temperature, strength, and porosity. For instance, in the bating process, a crucial step after unhairing, enzymes degrade residual proteins like albumin, elastin, globulin, and proteoglycan, resulting in softer leather, increased surface area, and better tanning preparation [79]. A study by Biskauskaitė et al. compared different bating enzymes (Zime SB, NovoBate WB, Oropon DVP, and Oropon WB) and found that proteolytic activity varied by enzyme type. NovoBate WB exhibited the highest proteolytic efficiency, making it particularly effective for this stage [81].

In summary, these chemical-enzymatic treatments are more suited for producing collagen hydrolysates for low-value applications (e.g., fertilizers, animal feed), but their economic viability increases when used to produce high-purity collagen or protein-based adhesives and films, which can command better market prices.

3.3. Recycling of the waste material

Mechanical recycling of leather waste into reinforcing fillers for polymeric composites or conversion into collagen fibers is one of the most cost-effective and low-energy strategies currently available. Considering cost-effectiveness is significantly improved by regional circular economy models, where leather waste from local tanneries is directly transformed into products in nearby industries (e.g., footwear, construction, automotive), thus reducing transportation and processing overheads.

3.3.1. Conversion into collagen fiber

The extraction of collagen fiber from leather waste involves a direct and indirect method, as depicted in Fig. 7. In the direct method, the collagen fiber is extracted mainly from scraps and sludge of non-chromium-tanned leather waste by using acids, alkalis, and enzymatic hydrolysis to obtain the collagen product [82]. Amongst all, the alkali hydrolysis process has demonstrated good economic feasibility in terms of industrial scale. In addition, studies have shown that extraction by acid hydrolysis produces significant yields. For example, a study performed by Masilamani et al. deduced that collagen fiber can be extracted from raw trimmings of goat skins by solubilization with acetic and propionic acid. The results showed high yields of collagen fiber extracted up to 93 % [83]. However, a combination of two or more hydrolysis methods is best for extracting collagen fibers from leather waste.

On the other hand, the indirect method of collagen fiber extraction consists of the use of chromium-tanned leather waste first by dechromisation, followed by the extraction of collagen fiber. This process has proven to be more complex since the separation of chromium from the leather waste is primarily followed by the extraction of the collagen fibers. Several dechroming methods have been established with high efficiency, which include acid, alkali, and enzymatic hydrolysis dechromisation, as well as dechroming by oxidation. (1) Dechroming by acid hydrolysis involves the use of strong acids under controlled conditions where Cr(III) in the chromium-tanned leather waste binds with functional groups of the acids, thereby forming soluble complexes, promoting the release of the collagen fibers from the cross-linked network.

Research studies have proven that inorganic (phosphoric, hydrochloric, and sulfuric acids) and organic acids (citric, oxalic, and formic acids) have been applied for the dechromisation of chromium and then the extraction of collagen fibers [84,85]. A study by Islam et al. investigated the dechroming of chromium from leather waste using concentrated H_2SO_4 , followed by treatment of the sample in HCl and EDTA combination, then keeping the obtained powder fibers in acetic acid for a day. Results showed high yields of collagen powder fiber [86]. (2) Alkali hydrolysis has also been applied for the dechroming of chromium from leather waste. Studies have shown the typical use of CaO, MgO or NaOH to solubilize Cr(III), followed by alkali precipitation from collagen fibers to insoluble $Cr(OH)_3$ [87]. However, CaO has proven to be one of the cheapest reagents among the commonly used alkalis, which has also been applied on an industrial scale [88]. In a recent study, Ding et al. developed a mild acid-alkali combined system for the dechromisation process of leather waste, achieving high dechroming and low hydrolysis of collagen fibers by using sodium hydroxide, urea, sulfuric acid, and calcium hydroxide. The results depicted a high dechroming efficiency of more than 97 % with low hydrolysis of 10 % for collagen fiber [89]. (3) Dechroming by enzymatic hydrolysis has proven to be an eco-friendly method with low secondary pollution and the amount of hydrolyzed collagen. In addition, this method is attributed with advantages such as strong specificity, mild reaction conditions, and low energy consumption compared to acid or alkali

hydrolysis. Notwithstanding, combining enzymatic hydrolysis with an acid or alkali has proven to significantly enhance dechroming efficiency. In a research study by Qiang et al., they explored a combined method of enzymatic and alkali hydrolysis to dechrome chromium from leather waste to obtain collagen fibers. CaO and MgO, in combination with 1398 neutral protease enzyme, were investigated and optimized for the removal of chromium and extraction of collagen fiber [90]. However, using a combination system of CaO and industrial trypsin has proven to be more suitable for dechroming and extraction of collagen fibers from chromium-tanned leather waste [82]. (4) Oxidation dechroming is another important dechromisation technique that consists of reacting peroxide compounds with the chromium-tanned leather solid waste to convert Cr(III) into the soluble Cr(VI) in a weak alkaline medium, thereby separating collagen fibers. Research by Yuan et al. investigated the use of H_2O_2 and NaOH at 50 °C for the oxidation dechroming of chromium-tanned leather shavings. Results showed that the dechroming efficiency was approximately 97.39 % after four dechromisation cycles [91]. According to literature, Cr(VI) is toxic, which is a by-product obtained from oxidation dechroming that presents as a hazardous pollutant. Therefore, research development towards new alternative methods of dechromisation with recent findings using pyrolysis [92–94] and dechroming of biochar [95].

3.3.2. Utilization as fillers in polymer-based composites

Considering the increasing demand for eco-friendly composite materials, the focus on promoting environmental sustainability, especially in the leather industry, is imminent. The waste generated from leather manufacture is generally disposed of in landfills and is hazardous. However, by applying new materials and technologies, continuous efforts towards transforming waste into valuable products have been gradually increasing over the last decade. Overall, polymer matrices have proven to be ideal for integrating leather waste. Since they possess the ability to entrap the leather waste, particularly chromium-tanned materials acting as filler, which prevents the oxidation of Cr(III) to Cr(VI) ion [96]. This helps prevent the formation of these carcinogenic compounds, thereby enhancing the environmental safety of the waste generated from the leather industry. Chromium-tanned leather waste acts as a reinforcing filler, increasing the mechanical stability of the final composite. In a recent study, Ribeiro et al. investigated the development of a cost-thermal insulating polymer composite prepared by mixing styrene-butadiene rubber and shavings of chromium-tanned leather waste. The results showed that the thermal insulation of the prepared polymer composite was higher than that of conventional building materials such as building boards, plywood, and fiberglass [97]. In another study, Mim et al. used chromium-tanned leather shaving in combination with polyvinyl alcohol to produce nontoxic, biodegradable composite packaging materials [98]. Taking into account that the tanning industry contributes highly to environmental hazards due to its vast usage, the application of waste materials has been applied in the fabrication of different polymer composites, thereby valorizing the large amount of solid waste generated from this sector, which promotes a sustainable

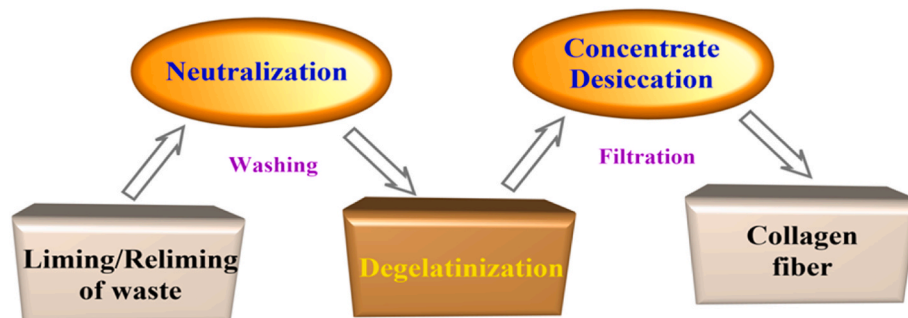


Fig. 7. Schematic representation of the process for the industrial extraction of collagen by means of alkaline hydrolysis.

economy with environmental safety [99]. The development of polymer-based composites by integrating leather waste particulate not only provides an alternative to recycling these materials but also broadens the potential applications of this waste material, thereby contributing to the advancement of sustainability goals. This approach gradually creates a more environmentally safe-oriented world, where most of our hazardous wastes are repurposed to develop valuable and functional products.

4. Characterization of leather wastes

4.1. Chromium and nitrogen content

Leather materials, composed primarily of collagen fibers with a distinctive triple-helix structure, have become indispensable in daily life. This structure arises from the assembly of three polypeptide chains, with collagen fibers containing seven distinct polypeptide variants that enable diverse molecular configurations [100,101]. Through pyrolysis, these collagen molecules can be transformed into nitrogen-doped carbon materials [3,101]. The nitrogen atoms in these structures are particularly valuable for adsorption and catalytic applications due to their lone electron pairs [38]. Converting chromium-tanned leather waste, a major source of environmental toxins, into functional materials thus offers both economic and ecological benefits [102]. Recent studies have focused on pyrolyzing chromium-tanned leather waste to produce nitrogen-rich carbon materials with high surface areas, enhanced conductivity, and superior adsorption capacity. These sustainable derivatives are cost-effective and suitable for diverse applications, including water treatment, energy storage systems, magnetic shielding materials, and footwear components [103,104].

Cr, typically applied as Cr(III) sulfate during tanning, plays a critical role in leather production. Cr ions bind to collagen fibers, improving material stability, flexibility, and environmental resistance through crosslinking [105]. However, pyrolyzing chromium-tanned leather generates Cr(III) oxide nanoparticles (50–200 nm), with Cr concentrations potentially exceeding 10 wt% in the resulting char. At high temperatures and in oxidative conditions, Cr can convert to toxic Cr(VI), posing environmental and health risks. Fortunately, Cr(VI) can be mitigated during carbonization through proper process control [100, 106].

4.2. Morphology

Leather materials are primarily composed of collagen fibers that can be converted into carbon fibers through carbonization [35,107]. These carbon fibers may subsequently be processed into powdered form [107, 108]. The carbonization method critically determines the effectiveness of this waste-to-material conversion, as it directly influences the resulting material's properties [100,109]. During carbonization, volatile organic components are eliminated from the collagen matrix, yielding a porous structure characterized by hollow vesicle-like formations and an interconnected network of micro- and macropores. The porous architecture is significantly affected by the activation agent quantity, where excessive amounts may compromise pore formation and structural integrity [109,110].

4.3. Specific surface area

The specific surface area of a material, defined as its total surface area per unit mass or volume, is a fundamental property that determines its suitability for applications such as adsorption, catalysis, and electrode materials for supercapacitors and batteries [30,111]. While untreated carbonized char typically exhibits a low specific surface area ($<10 \text{ m}^2 \text{ g}^{-1}$) [100], activation processes can dramatically increase this value to several hundred $\text{m}^2 \text{ g}^{-1}$ [112]. This enhancement occurs because activation creates porous structures that expand the carbon's

accessible surface area, thereby improving electron transfer and boosting electrochemical properties like capacitance [102]. The resulting surface area depends critically on several factors, including pyrolysis temperature, activation agent type, and processing duration [109].

Leather waste (LW)-derived activated carbon offers a sustainable alternative with competitive specific surface areas ($200\text{--}1600 \text{ m}^2 \text{ g}^{-1}$), compared to commercial activated carbon (CAC) from coal or coconut shells (up to $2271 \text{ m}^2 \text{ g}^{-1}$) (Table 1). LW-based materials possess distinct advantages, including: (1) a bimodal meso/microporous structure that facilitates ion diffusion, and (2) inherent nitrogen content from collagen that enhances wettability and introduces pseudocapacitance - features absent in unmodified CAC. These characteristics make LW-derived activated carbon particularly valuable for electrochemical applications (see Table 2).

4.4. Electrochemistry and magnetic features

Carbonized porous materials derived from leather waste have found broad applications across multiple fields, including energy storage [118, 119], biomedicine and electronics [120], and biotechnology [121]. Particularly in energy applications, the growing demand for clean energy solutions has made supercapacitors increasingly attractive due to their exceptional characteristics: long cycle life, cost-effectiveness, high power density, and environmental friendliness. Leather-based carbonaceous materials are emerging as promising active materials for electrochemical applications (Fig. 8). Electrochemical performance evaluation of these supercapacitors typically involves three key techniques: galvanostatic charge-discharge (GCD) analysis, cyclic voltammetry (CV), and electrochemical impedance spectroscopy (EIS) [118]. Supercapacitor testing employs two primary cell configurations: (1) Three-electrode cells - primarily used to assess material pseudocapacitance. (2) Two-electrode cells - better representing actual device performance. Cyclic voltammetry reveals the electrical properties of the material, with ideal supercapacitor behavior indicated by rectangular voltammograms. While most bio-derived carbons lack magnetic properties, leather-derived carbon exhibits notable ferromagnetism when pyrolyzed at $1000 \text{ }^\circ\text{C}$ for 8h, achieving magnetic saturation up to 5 emu g^{-1} . This magnetism originates from inorganic impurities (Fe: 0.8 wt%, Ni: 0.125 wt%, Co: 0.0005 wt%) introduced during processing. Furthermore, tannery sludge pyrolysis leads to the formation of chromic oxide structures (e.g., $\text{Mg}_2\text{Cr}_2\text{O}_4$, CaCrO_4) within the carbon matrix, contributing to these unique magnetic properties.

5. Applications in energy materials

The leather industry generates substantial quantities of solid and liquid waste, creating significant environmental and public health concerns. Converting these leather processing byproducts into valuable materials offers a dual benefit: reducing pollution while providing economic value to energy sectors. This transformation addresses two critical contemporary challenges: the growing global energy demand and the rapid depletion of fossil fuel reserves. These pressing issues highlight the urgent need to develop clean, sustainable energy alternatives that minimize environmental impact. In response, researchers are actively developing cost-effective materials for electrochemical energy storage systems, including batteries, supercapacitors, solar cells, and fuel cells - each offering distinct energy and power density characteristics Fig. 9 [37,118].

5.1. Supercapacitors

Supercapacitors represent a highly promising electrochemical energy storage technology, distinguished by their exceptional long-term performance characteristics [111]. These devices offer numerous advantages including high energy density, rapid charge/discharge capabilities, extended lifespan, and reliable operation. Current

Table 1
Specific surface area of various activated carbons derived from leather waste.

Precursor	Activation Temp. (°C)	Activation Agent	S _{BET} m ² g ⁻¹	Volume (cm ³ /g)	References
Solid leather waste	750	KOH	1602	0.249	[112]
Chromium-tanned leather shavings	600	ZnCl ₂	821	0.333	[30]
	600	H ₃ PO ₄	505	0.120	
Vegetable-tanned leather shavings	600	ZnCl ₂	1274	N.D.	
	600	H ₃ PO ₄	543	N.D.	
Chromium-tanned pigskin leather wastes	800	KOH	1180	0.507	[35]
Leather waste	700	H ₄ P ₂ O ₇	381	N.D.	[107]
Leather-derived carbon aerogels	800	KOH	2523	N.D.	[109]
(Cr, N)-co-doped carbon cloth	900	(NH ₄) ₆ Mo ₇ O ₂₄ ·4H ₂ O	282	0.156	[113]

N.D. not determined.

Table 2
Comparison of leather-derived porous activated carbon as material for supercapacitors.

Precursor	Electrolyte	Specific capacitance (F g ⁻¹)	Energy density (Wh Kg ⁻¹)	Cycle stability	Reference
Footwear leather waste	0.5M H ₂ SO ₄	268	12.8	5000 cycles, 92 %	[114]
Blue leather solid waste	1M Na ₂ SO ₄	2203	624.7	10000 cycles	[115]
Chromium-tanned leather shavings	6M KOH	333.5	N.D.	5000 cycles, 93.5 %	[37]
Leather-derived carbon aerogels	N.D.	132.22	N.D.	1000 cycles, 99 %	[109]
Mn-doped N-containing carbon from collagen fiber	1M KOH	272.62	N.D.	6000 cycles, 81.4 %	[116]
Vegetable-tanned leather shavings	1M KOH	421	12.2	5000 cycles, 83 %	[104]
Raw leather trimming waste	1M H ₂ SO ₄	108	6.95	10000 cycles, 91 %	[117]
Leather waste	6 M KOH	550	N.D.	2000 cycles, 82 %	[107]
Crust leather waste	1M KCl	1960	N.D.	N.D.	[36]

supercapacitor technologies primarily fall into three categories: electrochemical double-layer capacitors (EDLCs), pseudocapacitors, and hybrid capacitors (Fig. 10) [117,123]. Activated carbon serves as a crucial electrode material due to its excellent adsorption properties, high surface area, and cost-effectiveness. The performance characteristics vary significantly depending on the precursor materials. While chromium-tanned leather waste containing heavy metals may be unsuitable for water treatment applications, its substantial surface area makes it particularly effective for supercapacitor electrodes [102,124,125]. Compared to bio-based activated carbons (e.g., from polylactic acid), leather waste-derived carbons offer superior cost-effectiveness, higher surface areas, and significant nitrogen content, making them ideal for energy storage applications. Chemical activation methods can produce activated carbons with exceptionally high surface areas. For instance, Ma et al. developed chromium-tanned leather-based hierarchical porous carbon with a remarkable surface area of 3211 m²g⁻¹ and pore volume of 2.02 cm³g⁻¹ [37]. In contrast, chromium-free

counterparts showed reduced values (2182 m²g⁻¹ and 1.40 cm³g⁻¹), suggesting chromium oxide's role in creating additional activation sites and enhancing porosity. Kennedy et al. further demonstrated the exceptional electrochemical performance of wet blue leather-derived activated carbon, achieving a specific capacitance of 2203 F g⁻¹ with excellent cycling stability [115]. These results surpass commercial carbon materials, highlighting leather waste's potential for high-performance supercapacitors. As shown in Fig. 10, the electrochemical properties vary according to precursor materials, enabling tailored performance for specific applications.

5.2. Batteries

Leather-derived carbons have demonstrated significant potential as electrode materials for advanced battery systems. When carbonized at 1000 °C for 8h, these materials function effectively as cathodes in lithium-ion batteries [100]. Electrochemical evaluations using a 1M LiPF₆ electrolyte (1:1 v/v ethylene carbonate:dimethyl carbonate) with Li foil reference electrodes revealed an initial specific capacity of 400 mAh g⁻¹ for leather-derived carbon cathodes, stabilizing at 327 mAh g⁻¹ after 50 cycles [126]. The unique collagen-based nanostructure of leather waste carbons provides superior lithium storage capacity compared to conventional graphite or graphene, owing to structural defects that facilitate lithium-ion transport while preventing performance-limiting layer formation. As anode materials, leather shaving-derived carbons exhibit remarkable performance, delivering 735 mAh g⁻¹ at 0.5 A g⁻¹ over 1000 cycles [127], highlighting their promise for sustainable energy storage applications. Activation methods significantly influence material performance. Nitrogen-doped activated carbons prepared via KOH activation achieve superior characteristics (2247.45 m²g⁻¹ surface area, 534.8 mAh g⁻¹ capacity after 100 cycles) compared to CaCO₃-activated counterparts (249.93 m²g⁻¹, 261.4 mAh g⁻¹) [128], demonstrating the critical role of activation chemistry in electrochemical performance. The application extends to sodium-ion batteries, where pyrolyzed cow leather (1100 °C, 3h) yields hard carbon anodes with 207.9 mAh g⁻¹ capacity [129]. Carbonized cow leather was pyrolyzed at three temperatures (700 °C, 1100 °C, and 1500 °C) for 3 h (Fig. 11a). The 1100 °C derived hard carbon exhibited optimal performance, demonstrating a high specific capacity of 207.9 mAh g⁻¹. Composite materials further enhance sodium-ion battery performance; for instance, MoS₂/NP-C doped composites have shown promise as high-performance anodes (Fig. 11b) [129]. Researchers have also explored various doped carbon architectures, including single-element (B-, N-, S-, P-), dual-, and triple-doped carbons for these applications (Fig. 11c).

5.3. Fuel cells

Fuel cells represent one of the most efficient energy storage and conversion systems, offering near-zero emissions during operation. Among the various types, including proton exchange membrane (PEM), solid oxide, alkaline, phosphoric acid, molten carbonate, and direct

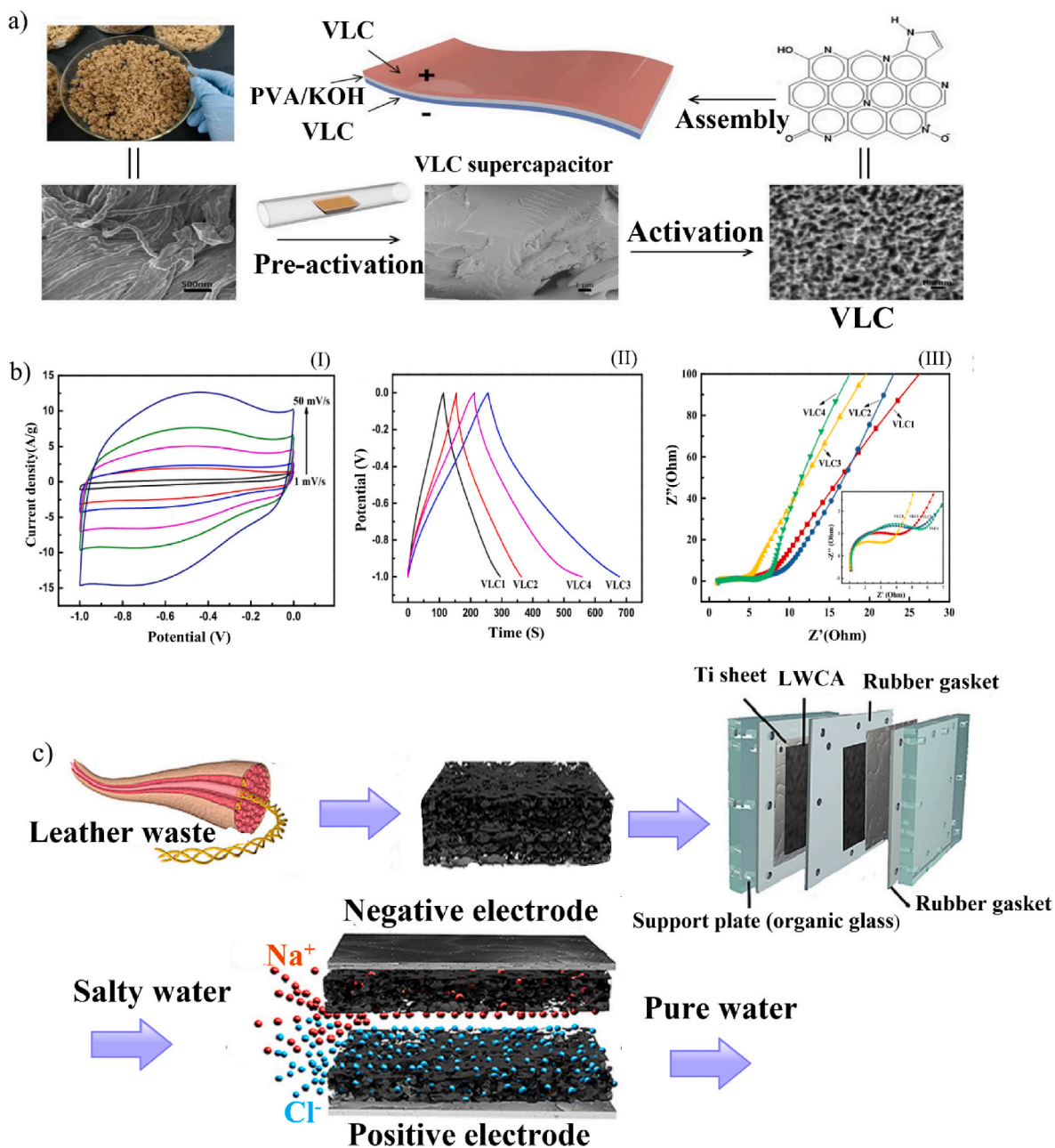


Fig. 8. (a) Fabrication of electrodes for supercapacitors [104], (b) i. CV curves with scan rate from 1 to 50 mV/s, (ii) electrochemical impedance spectroscopy with frequency 0.01–100 Hz, (iii) GCD and (c) activation of leather waste [109].

methanol fuel cells, PEM fuel cells have achieved commercial success in both stationary and automotive applications [132]. These systems rely critically on hydrogen and oxygen as key reactants for electricity generation through electrochemical processes [133]. At the cathode, where oxidation-reduction reactions occur, conventional platinum-carbon (Pt/C) catalysts remain prohibitively expensive. To address this challenge, researchers are developing alternative metal-based catalysts using iron and cobalt combined with heteroatom-doped carbon systems, which have shown promising efficacy as Pt replacements [134–136]. Recent advances include the work of Soni et al., who synthesized platinum-free electrocatalysts from leather waste. Their process involved creating heteroatom-doped carbon catalysts by combining acid-treated leather waste with FeCl_3 , followed by annealing at 800 °C, 900 °C, or 1000 °C. These temperatures significantly influenced the catalyst's active sites, porosity, and overall structure [120,132,137]. Microbial fuel cells present another sustainable approach,

simultaneously addressing leather waste management and renewable energy production. These systems can reduce toxic Cr(VI) to less harmful Cr(III) while generating electricity [138].

5.4. Solar cells

The leather industry produces significant quantities of chromium-rich byproducts, particularly chromium-tanned leather shavings containing 3000–6000 ppm Cr(III) [139]. These waste materials, composed of chromium oxide (Cr_2O_3) and collagen fibers, show exceptional promise for organic semiconductor applications due to chromium's electrochemical enhancement properties [140]. Recent research by Murugan et al. demonstrated the synthesis of a composite material from Cr_2O_3 , TiO_2 , and activated carbon derived from chromium-tanned leather buffing waste. The activated carbon component serves as an ideal support matrix owing to its high surface area and porous structure,

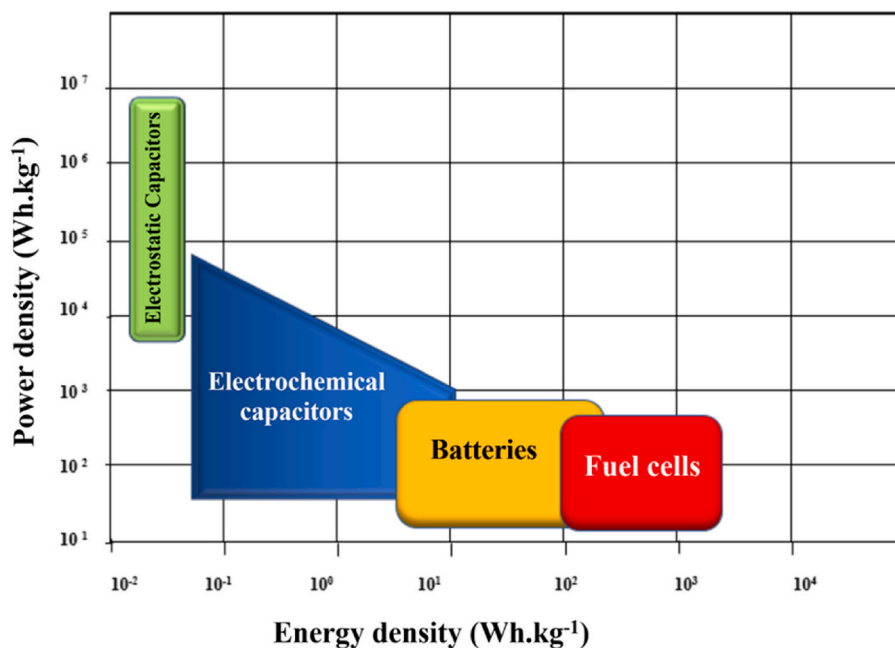


Fig. 9. Ragone plot of specific energy density versus specific power density for various energy storage systems.

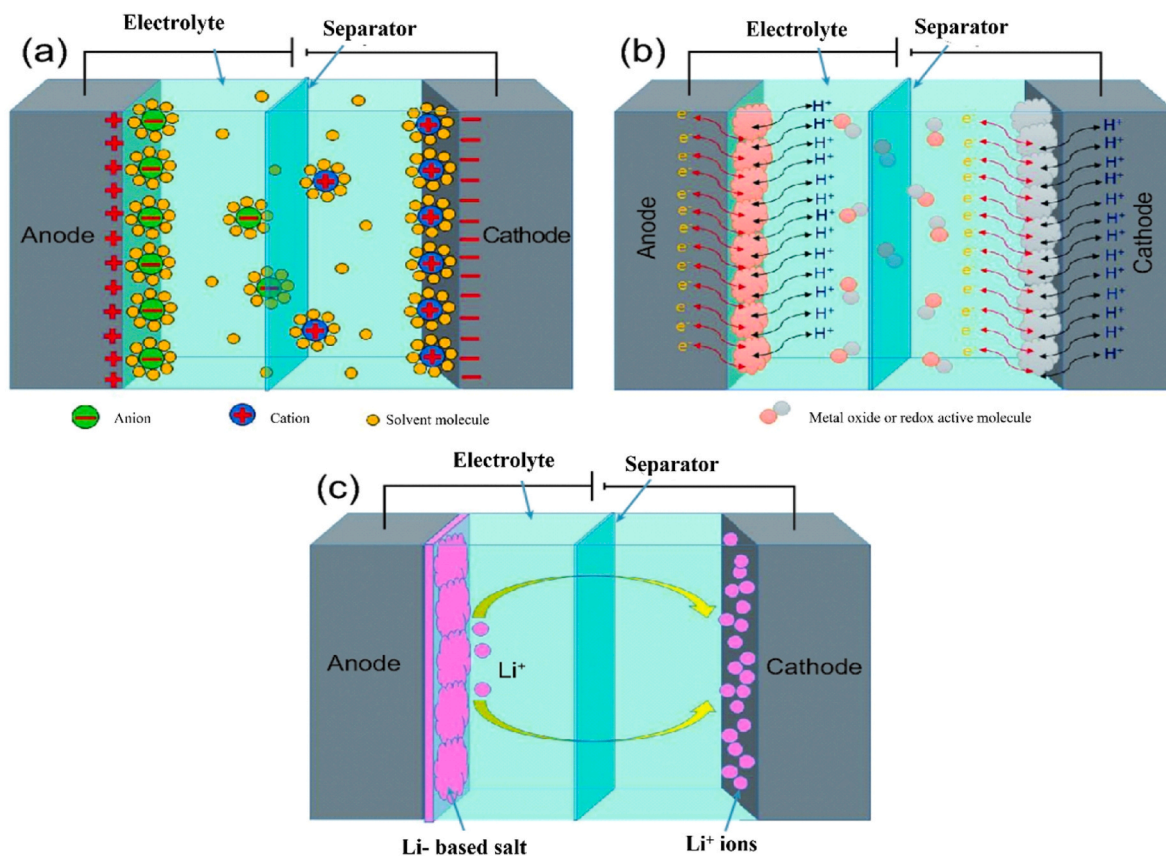


Fig. 10. Schematic representation of (a) an electrical double layer capacitor, (b) a pseudo capacitor, and (c) a hybrid supercapacitor. (Reproduced with permission from Ref. [122] Oxford Academic, copyright 2017).

which promotes uniform composite dispersion and structural stability. These characteristics significantly enhance the material’s photocatalytic performance and durability across multiple cycles [141,142].

6. Life-cycle assessment perspective

To assess the potential environmental impacts of competing energy material technologies, it is crucial to evaluate how these products are developed using standardized frameworks, such as Life Cycle

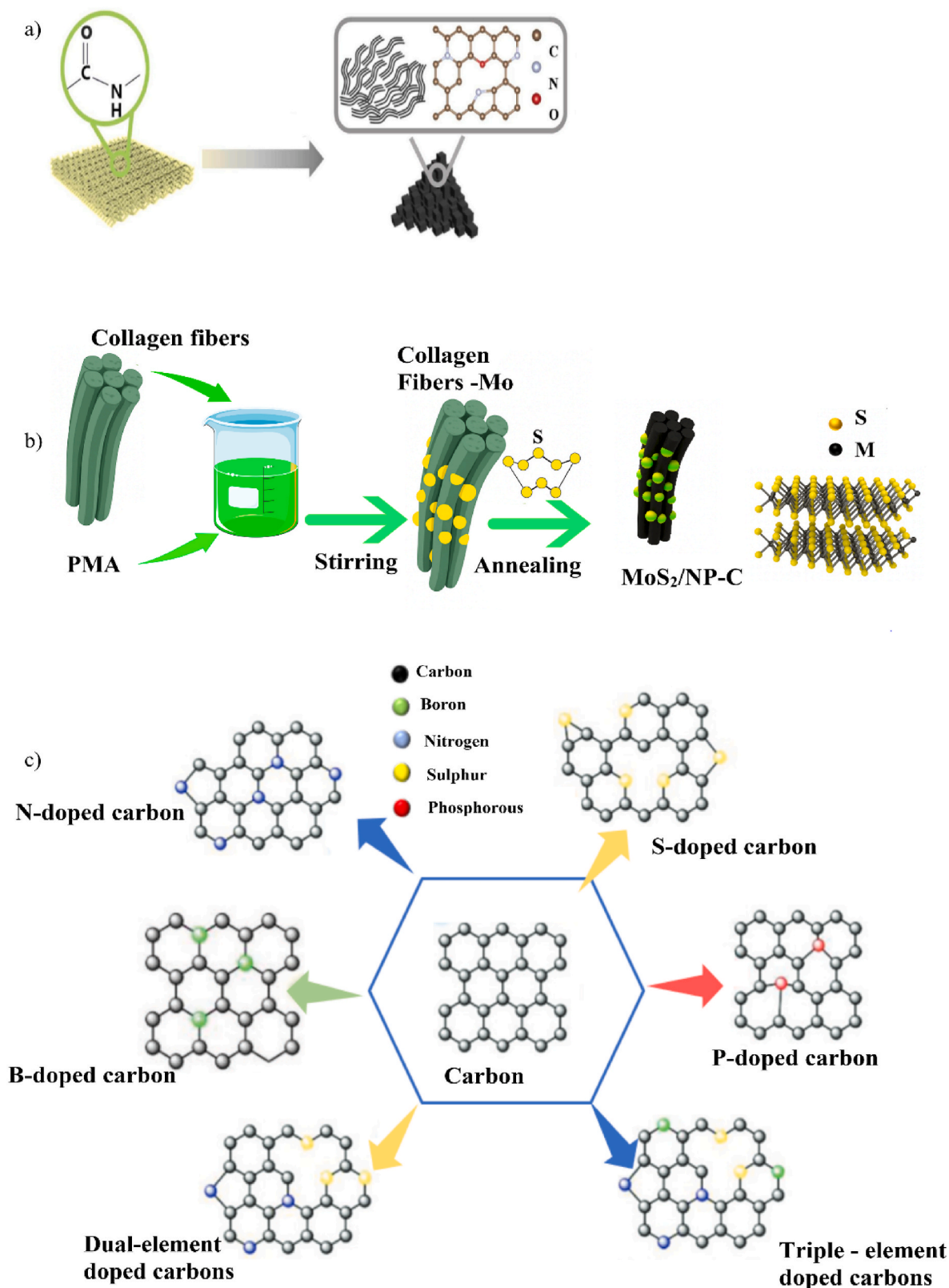


Fig. 11. (a) Synthesis of hard carbons for sodium-ion batteries, (b) fabrication of MoS₂/NP-C-2 composites for SIBS, and (c) a diagram of the geometries of different heteroatom-doped carbons. Adapted with permission refs [129–131].

Assessment (LCA). LCA involves a systematic approach consisting of key methodological steps: defining the goal and scope, conducting an inventory analysis, performing an impact assessment, and interpreting the results (Fig. 12) [143]. This comprehensive methodology provides

insights for directing energy material research and development efforts toward minimizing environmental hazards. It also evaluates the projected environmental impacts of large-scale applications, such as energy grids or vehicle systems.

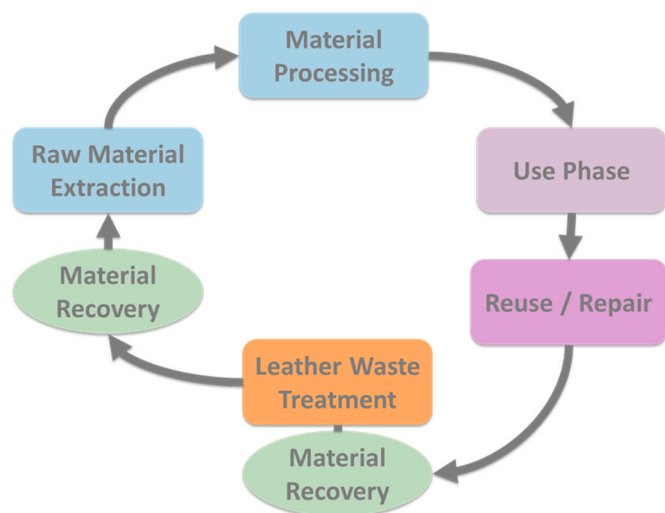


Fig. 12. Key steps in the environmental assessment of energy materials based on LCA.

The leather industry exerts a significant environmental burden, primarily due to its intensive water and chemical usage. One of the most critical concerns is the use of chromium compounds in the tanning and dyeing processes, which are known to pose considerable environmental and health risks [20]. Life Cycle Assessment (LCA) studies consistently highlight the substantial negative impacts of conventional leather production methods on both human health and ecosystems, underscoring the urgent need for improved waste and emission management strategies [144].

In response to these challenges, the industry has begun adopting innovative tanning technologies designed to reduce its environmental footprint. These advancements focus on decreasing water and chromium usage without compromising the quality of the final leather product [145]. Cleaner production methods and more efficient wastewater treatment systems are proving effective in mitigating the environmental impacts of leather manufacturing [145,146]. Furthermore, voluntary sustainability measures such as eco-labeling schemes and third-party audits are playing a vital role in promoting transparency and encouraging best practices across the sector.

Table 3 below presents a selection of peer-reviewed studies from 2016 to 2024 that apply LCA to evaluate environmental impacts across various leather production and waste treatment pathways. These studies cover a range of topics, ranging from recycling and biorefining of leather waste to innovations in low-chromium tanning and wastewater treatment, and highlight both methodological advances and practical sustainability improvements. Each entry summarizes the scope, and key findings.

Despite the longstanding use of LCA, previous studies have often limited their focus to one or two parameters, primarily addressing the environmental hazards associated with raw material extraction and processing. However, these studies frequently overlook key aspects, such as the primary and secondary use of materials and the recycling of final products. Moreover, recent research has not thoroughly examined the differences between average, marginal, and incremental sources of key raw materials. While the recycling of energy materials has been more extensively studied than their manufacturing processes, LCA analyses of recycling often rely on approximated or simulated mass and energy balances. This is due to the relatively low recycling rates for these materials [152,153]. This gap in the literature highlights the need for studies that leverage existing data and market projections to provide a more holistic understanding.

Table 3

Evaluation of environmental impacts in different leather production and waste treatment pathways using LCA.

Scope	Key Highlights	References
Leather recycling in circular economy	Discussed systemic challenges and impact reduction in leather reuse and recycling	2016 [60]
Protein hydrolysate from leather waste	Compared chemically vs enzymatically derived proteins; showed environmental gains from reuse	2017 [147]
Review on LCA of leather production and waste	Highlighted 4 LCA studies on waste valorization and emphasized need for more data	2020 [148]
Tannery wastewater treatment via EC-UV	Demonstrated 94 % COD removal and significant toxicity reduction in treated water	2020 [149]
Biorefining of leather solid waste	Reviewed LCA-linked recovery of energy and chemicals; identified research gaps	2022 [150]
Revalorization of chromium-tanned leather shavings	Developed carbon materials and re-tanning agents; LCA supported benefits	2023 [6]
Biogas production from chrome-tanned waste	Experimental and kinetic evaluation with potential for circular valorization	2024 [151]
Low-chromium, low-water leather tanning processes	Compared environmental performance of 3 innovative tanning methods using LCA; reduction in chromium and water use	2024 [145]

7. Future research outlook

The rapid growth of the leather industry has heightened environmental concerns, prompting researchers to seek effective ways to minimize waste generation in this sector. Recent studies have identified challenges in implementing circular economy practices to reduce leather industry waste. Key obstacles include limited financial support from governmental authorities and insufficient technological advancements in waste reduction strategies [154,155]. However, ongoing research into mitigating the environmental hazards of chromium tanning has shown promise, particularly through the extraction of chromium from leather waste and the pyrolysis of waste to produce activated carbon materials suitable for energy applications.

Chromium tanning remains the preferred method due to the desirable properties it imparts to finished leather products. However, eco-friendly alternatives, such as ultrasound-assisted and salt-free Pickering chrome tanning, have shown potential while maintaining leather quality [156,157]. Despite these advancements, certain challenges persist. For instance, microwave- and ultrasound-assisted chromium tanning techniques have demonstrated lower thermal stability and non-uniform chromium distribution compared to conventional methods [158].

In response to these challenges, environmentally friendly, chromium-free tanning alternatives are gaining attention. These approaches utilize various tanning agents, including natural and synthetic amino acids and metal salts, which have produced leather with properties comparable to chromium-tanned leather [159,160]. Although these methods are promising, further research is needed to optimize their effectiveness and reduce the environmental footprint of the leather tanning industry [161].

When considering the use of chromium-tanned leather waste in energy materials, limited investigations have been conducted. Exploring methods to extract and quantify Cr (III) and Cr (VI) from leather waste presents a valuable opportunity to convert this waste into high-value products while minimizing its environmental impact. Developing protocols for facile interconversion processes, alongside established techniques like pyrolysis, could enable the production of conductive

composite materials for energy storage systems. Advancing these strategies represents a significant milestone in mitigating environmental challenges and expanding the applications of leather waste in sustainable energy technologies.

8. Conclusions

This review discusses the recent advances in the utilization of chromium-tanned leather wastes, focusing on studies published in the last few decades. These advances include improved treatment techniques and diverse applications of leather waste in the development of energy materials. Despite significant progress, challenges remain, offering new opportunities for research and innovation. Long-term efforts are essential to establish leather waste as a valuable resource for energy storage systems through in-depth exploration and application.

1. Dechromization remains a critical area of research due to the complexity of current processes. Oxidative dechroming methods, while effective, require multiple steps to achieve optimal extraction of Cr (III) and Cr (VI), making them highly sensitive and labor-intensive. However, chromium shavings have shown promise as precursors for active carbon materials, which exhibit excellent electrochemical performance in energy storage applications such as supercapacitors and batteries. Developing practical, efficient, and scalable raw material treatment methods is imperative to enhance performance and reduce processing challenges.
2. Chromium-tanned leather waste often lacks proper classification and treatment, complicating its resource utilization. However, studies have demonstrated the potential of these wastes in producing polymer-based and blended composites. Incorporating synthetic or plant fibers into regenerated leather composites has further expanded their applicability, particularly for energy materials. Modifications to enhance the electrochemical properties of these composites have shown promise for energy storage systems. Continued innovation is needed to optimize these materials and broaden their use in energy applications.

Considering the life-cycle assessment of chromium-tanned leather waste and its derivatives, sustained efforts are required to minimize waste generation and promote sustainable technologies. By developing versatile strategies for the application of leather waste in energy materials processing, researchers can address both environmental concerns and growing market demands. This will pave the way for the integration of leather waste into the rapidly evolving field of energy material technologies, ensuring sustainable and impactful utilization.

Informed consent statement

Not applicable.

Institutional review board Statement

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Investigation, Methodology, Writing – original draft, Writing – review & editing. **Fahanwi Asabuwa Ngwabebhoh:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Viera Pechancova:** Methodology, Validation, Writing – original draft, Writing – review & editing. **Tomas Saha:** Funding acquisition, Validation, Writing – review & editing. **Petr Saha:** Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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