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Tannery solid waste generation trend and sustainable management techniques for commercialization

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The global rise in leather consumption has led to a significant increase in tannery solid waste (TSW), especially in developing countries where inadequate treatment practices pose serious environmental and public health risks. This study reveals that TSW generation has surged more than 100-fold over the past six decades, with production shifting predominantly to Asia. In this review, as a representative developing country, we outlined the details of the TSW generation scenario for Bangladesh and sustainable approaches to manage them, as it faces disproportionately severe impacts despite contributing less than 1% of global TSW. The review identifies major challenges in current management practices, including the inefficiency of direct disposal methods and the limited scalability of conventional dechroming techniques. Critical findings show that emerging valorization approaches, such as biodiesel production from fleshing, enzyme-assisted anaerobic co-digestion, which boosted biogas build-up to 81%, and low-temperature gasification, offer environmentally sound and commercially viable alternatives. Likewise, pyrolysis and immobilization strategies demonstrate potential for both energy recovery and resource stabilization. The study also proposes a context-sensitive hypothetical circular economy model for TSW management, integrating technological pathways with socio-economic indicators to support long-term sustainability. Ultimately, this review offers strategic insights for transitioning from linear to circular waste management frameworks. It emphasizes the importance of policy reform, stakeholder collaboration, and future research focused on Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA). The proposed framework aligns with multiple Sustainable Development Goals, including SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), and SDG 15 (Life on Land), providing a pathway toward safer, inclusive, and globally certified tannery practices.

Highlights

• TSW output soared 100-fold in 60 years as tanning shifted heavily to Asia.

• Bangladesh contributes <1% TSW but faces extreme chromium pollution in soil and water.

• 6.2 kg of leather waste yields 1 L of biodiesel that meets EN 14214 standards.

• Co-digestion of TSW with organic waste increases biogas yield by up to 81%.

• Circular model integrates energy recovery and Cr stabilization with minimal pollution.

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1 Introduction

Rapid industrialization has significantly increased the size of the economy of several nations, such as China, India, Brazil, Bangladesh, Pakistan, Turkey, and Ethiopia. Among the key financial contributors in these nations, the tannery industry is recognized as one of the oldest and commercially significant sectors, particularly in terms of export revenue, regional development, and job prospects.[1] This industry produces non-putrescible stable leather from putrescible wet salted raw hides and skins through a complicated tanning process, as illustrated in (Fig. 1a), which comprises a series of unit operations, *e.g.*, pre-tanning or beam house operation, tanning, post-tanning, or finishing.[2,3] During the conversion of raw hides and skins into stable wet blue leather, basification plays a significant role, where basic chromium(III) sulfate forms larger polynuclear complexes by the formation of hydroxyl bridges

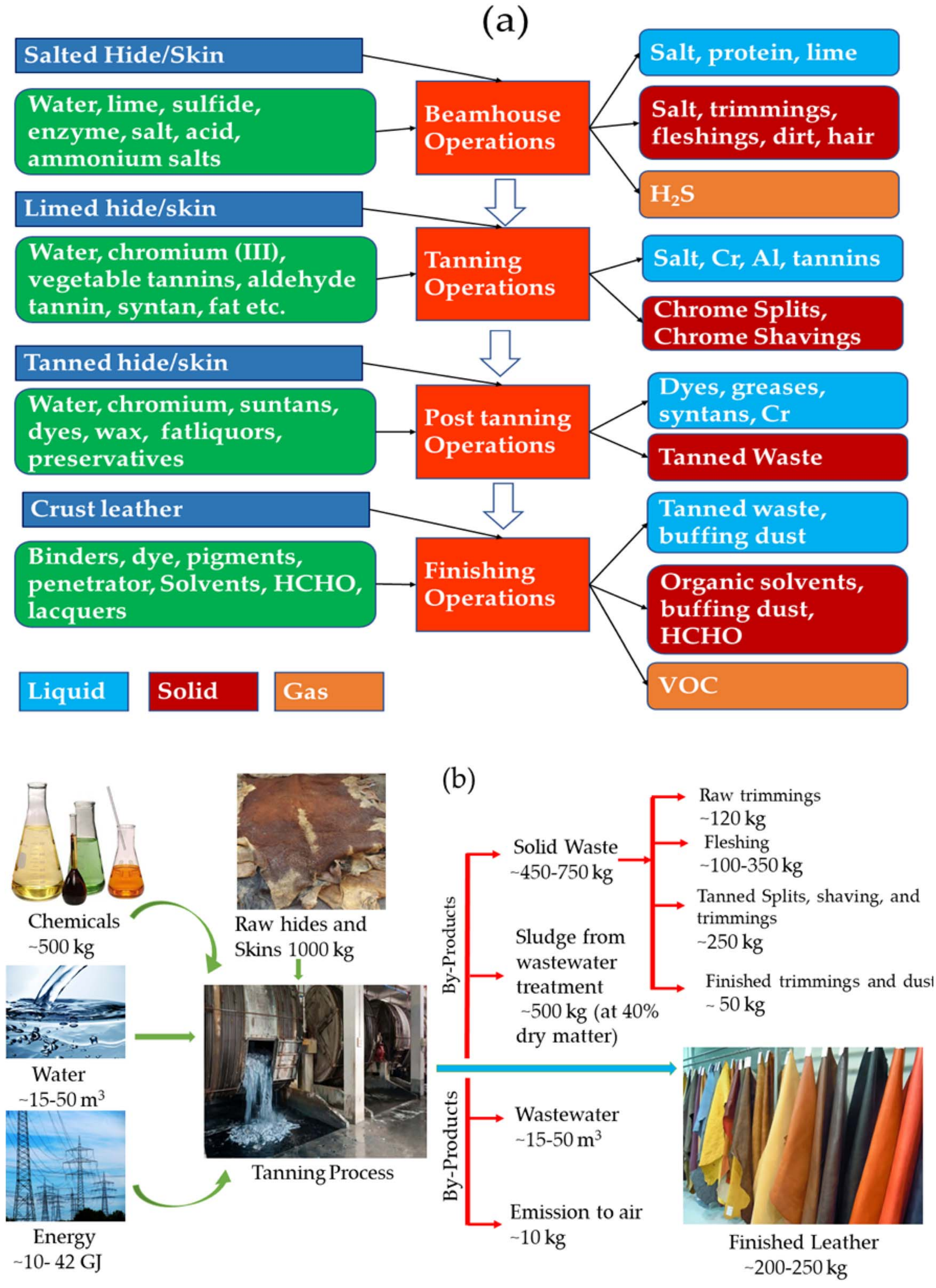

Fig. 1 Schematic diagram of tanning process (a) input and output of different unit operations and (b) overview of raw materials, chemicals, utilities, with finished leather, and pollution load.

between metal centers, followed by the development of oxo bridges between two neighboring chromium complexes. During the aging stage, unfixed and incomplete chemicals are generated, which leak as liquid from wet blue piles.

Tanning is a water-intensive and chemically demanding process, requiring approximately 15–50 m^3 of water and 500 kg of various toxic chemicals, including basic chromium(III) sulphate, to process 1000 kg of raw hide, as demonstrated in

(Fig. 1b).[4–6] However, only 20% of the raw material is converted into stable leather, and produces about 800 kg of TSW.[7,8] Additionally, about 30–40% of the chemicals used in the tanning process are discharged into the environment either as solid or liquid waste.[4] TSW contains proteinaceous substances such as fat (3–6%), minerals (15%), and several types of proteins, mainly collagen protein (CP) (90%) and 3.5–4.5% of hazardous Cr_2O_3.[1,9,10] Previously, many efforts have been made to address solid waste pollution in the leather industry, relying solely on conventional methods such as landfilling, incineration,[11] and chemical treatment.[11–18] While these methods have shown some effectiveness, they often come with high costs, poor efficiency, and are labor-intensive. However, these methods may not fully address the environmental footprint of the tanning industry. Therefore, the majority of tanners in developing countries fail to meet SDG goals, which puts the leather working group (LWG) accreditation in jeopardy, endangering the oldest, traditional, and commercially important leather business.[19] To ensure the continued expansion and survival of the tannery business, a profitable, integrated, and sustainable circular-economy (CE)-based waste management solution is necessary to address the major issues of TSW and transform them into opportunities.

Over the past several decades, a wide range of sustainable TSW management techniques have been developed, including biological, thermal, and immobilization. To develop profitable, integrated, sustainable CE-based waste management techniques, a broader understanding of each sustainable TSW management technique, along with TSW generation trends, is crucial. Some recent studies summarize the knowledge of sustainable management of TSW, which includes the sustainable ways to recover CP,[20] disposal options, and utilization of TSW for tannery effluent treatment,[21] waste generation in the cleaner leather manufacturing technology,[22] heavy metals elimination from contaminated soil by phytoremediation,[23] anaerobic digestion to reduce waste and recover value-added products,[24] bacterial and fungal isolation of Cr^{6+} from soil and water,[25] direct and indirect dechroming,[26] opportunities to recover leather and challenges to achieve CE,[27] Cr recovery for the safer disposal of chrome-tanned solid waste (CTSW).[28] Production of adsorbent, biodiesel, biogas, biopolymers, and fertilizer from TSW,[29] enzymatic and microbial biotransformation of CTSW,[30] advancement of sustainable technologies for commercializing TSW,[31] and trends to produce value-added products from TSW.[1] Yet, there remains a significant gap in the literature addressing TSW generation trends, socioeconomic burdens, and scalable valorization technologies.

Putrescible raw hides, comprising 60–80% of dry skin content, are transformed into non-putrescible leather through pre-tanning, tanning, and finishing steps.[2] Beam house operations include trimming, desalting, soaking, unhairing, liming, bating, and pickling, releasing solid, liquid, and gaseous pollutants[32] as shown in (Fig. 1a). Tanning process stabilizes collagen with the aid of various agents including mineral (Cr^{3+}, Al^{3+}, Ti^{4+}, Zr^{4+}) and non-mineral (plant-based, oil-based, aldehyde, zeolite).[33] Chrome tanning (CT), dominant globally (~90% of production), produces both valuable leather and extensive waste.[34] Post-tanning involves splitting, shaving, and surface finishing using resins, binders, waxes, pigments, and cross-linkers,[35] which further contribute to environmental emissions.

Globally, ~150 million tons of raw hides were processed between 2012 and 2023, generating ~120 million tons of TSW at 800 kg per ton.[38,39] TSW generation rose ~200-fold from ~50.5

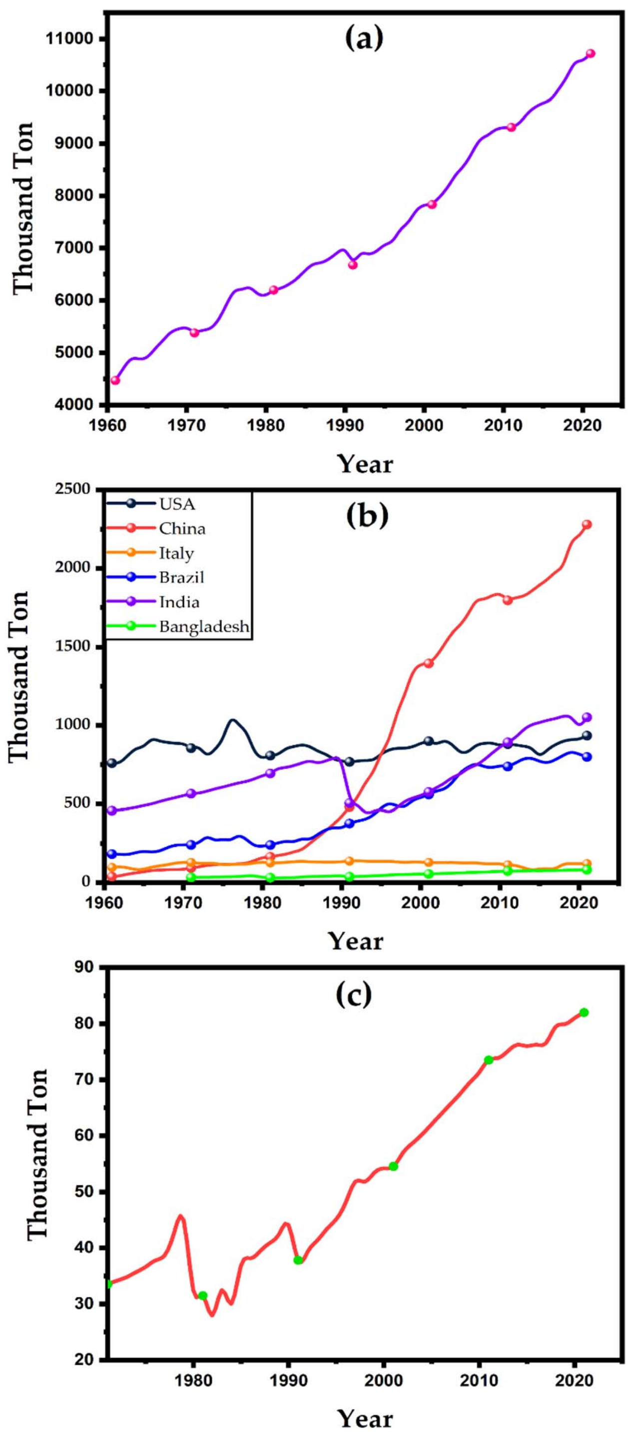

Fig. 2 TSW generation (a) world scenario, (b) key leather producing countries, and (c) Bangladesh.

million tons in 1961–1970 to current levels[40] (Fig. 2a). China leads in production, followed by Italy, Brazil, and India, while Bangladesh contributes 1–1.2% (Fig. 2b and c). The shift of global leather production to Asia (60%) coincides with tannery closures in Europe.[1,41]

The geographical distribution of TSW has undergone significant changes over the past three decades, with Asia emerging as the primary producer. China accounts for the lion's share of the world TSW, generating between 1.2 to 1.5 million tons annually, where major tannery clusters are located in Hebei, Zhejiang, and Guangdong provinces.[42] The waste management infrastructure in these regions is facing significant challenges in keeping up with the country's rapid industrial expansion. An estimated 0.8 to 1.0 million tons of TSW are produced annually in India, the second-largest producer in the world in recent years, with the majority of that production concentrated in Tamil Nadu, West Bengal, and Uttar Pradesh.[43] In contrast, developed countries like the USA once a major leather hub, showed a different TSW generation pattern. Despite being a large consumer of finished leather and leather goods, the US tanning industry has witnessed a sharp decline, with the majority of this waste coming from imported wet blue and crust leather rather than raw hides and skins processing.[44] US TSW generation has declined by approximately 40% since its peak in the 1970s due to stricter environmental regulations. Most of the tanneries (around 154) in Bangladesh carry out the chrome tanning process for shoe upper leather, and garment leather.[20,46]

Bangladeshi TSW production increased from 26 to 82 thousand tons between 1982–2021.[38] Currently, ∼238.79 tons/day of untreated TSW is generated and dumped into lowlands.[47] Hazaribagh ranked fifth among the world's most polluted areas in 2013 due to these practices.[48] Poor landfill design causes chromium and other toxins to leach into nearby soil, threatening agriculture.[49]

TSW disposal adversely affects the environment and public health, causing discoloration, oxygen depletion, and Cr^{6+}-linked toxicity, which triggers cancer, mutations, and teratogenic effects in humans and ecosystems.[4,50,51] Heavy metals (Cr, Pb, Cd, Zn, Mn) have accumulated in soils near tanneries in India and Bangladesh.[45,52–56] Leached salts raise soil alkalinity;[51] decaying organics lower water DO levels.[58] Cr exposure affects tannery workers and nearby residents through dermal, inhalation, and ingestion pathways, causing skin, liver, kidney, and respiratory diseases.[5,62–64] Cr^{6+} concentrations in topsoil near Savar CETP (3.8–39 200 mg kg^{-1}) exceed both background (0.6 mg kg^{-1}) and Dutch safety limits (100 mg kg^{-1}).[45] Dhaleshwari River sediments show Cr levels comparable to the Buriganga,[56,65] and effluent Cr levels in Hemayetpur (up to 780 mg L^{-1}) and Hazaribagh (374.19–52.5 mg L^{-1}) exceed Bangladeshi (0.5 mg L^{-1}) and FAO (0.1 mg L^{-1}) guidelines.[45,66,67] Alarming levels of Cr have been found in the nails and hair of tanners (21.85–483 mg kg^{-1}) and residents (6.01–21.89 mg kg^{-1}) in Hazaribagh,[46] underscoring the urgent need for sustainable TSW management and valorization of its collagen, fat, and hair content.

The leather industry produces a significant amount of TSW each year, increasing exponentially over the last six decades as described above, making it one of the fastest-expanding yet least-managed industrial waste streams worldwide [Fig. 2b]. This escalating crisis directly threatens millions of people living near tannery clusters in developing countries, where unmanaged TSW contaminates groundwater, degrades agricultural soils, and exposes communities to carcinogenic compounds through multiple pathways. Without sustained academic attention to technology development, policy frameworks, and implementation strategies, the TSW crisis will intensify further. Considering the current realities of TSW mismanagement and its critical consequences for public health, ecosystems, and economic sustainability, this study brings together a wide range of practical insights on sustainable tannery waste solutions.

It moves beyond conventional treatments to explore promising, commercially relevant technologies from biological digestion and chemical recovery to immobilization and energy valorization that offer realistic pathways for transforming waste into value. The review further outlines a conceptual circular economy-based framework for TSWM, anchored in the local context and aligned with global goals, while also reflecting on the social dimensions that often go overlooked. By presenting feasible, context-sensitive strategies, the study hopes to encourage researchers, industry actors, and policymakers to work together toward a more responsible, inclusive, and environmentally sound leather industry. Ultimately, it aims to contribute to the transition from waste burden to resource recovery, supporting cleaner production, meeting SDG targets, and paving the way toward broader LWG accreditation in the global South.

2 Research methodology

To understand the evolving landscape of tannery solid waste management (TSWM) and its practical implications, this investigation followed a structured yet context-sensitive literature review process. A wide range of sources, including journal articles, review papers, books, technical reports, and documents from government bodies, NGOs, and international organizations, was explored. Initially, over 500 documents were retrieved from the Scopus database using a diverse set of research keywords including leather tanning process, chrome tanning, tannery solid waste, chrome tanned waste, untanned leather waste, health and environmental impacts of tannery waste, tannery solid waste management, tannery solid waste valorization, sustainable tannery solid waste management, chromium recovery, collagen recovery, fat extraction from leather waste, biological, chemical, and thermal treatment of tannery solid waste, leather waste to product, fertilizer, biogas, biodiesel, and gelatin. Through a careful process of reading, sorting, and shortlisting based on relevance, coherence, and clarity, around 250 works were finalized for in-depth analysis. Peer-reviewed journals in the fields of environmental and pollution science, chemical and process engineering, leather science and industrial technology, biotechnology, materials and composite sciences, bioenergy, sustainability, and socio-economic or environmental impact studies were included. Besides, non-peer-reviewed publications like technical reports, government publications, and industry publications have also been used ensuring credibility, where these publications have provided essential operational and process-specific information, which was not readily available in the scientific literature. Predatory journals and publications lacking methodological rigor and relevance to tannery solid waste management have been excluded. Particular emphasis was placed on materials published after 2010 to ensure the discussion reflected recent advances, although studies dating back to 1980 were consulted to trace foundational developments. The review process combined manual scrutiny with the use of analytical tools such as Bibliometrix for bibliographic mapping, EndNote for reference organization, and OriginPro and Adobe Illustrator for generating figures and diagrams. Priority was given to highly cited papers and practically grounded innovations that offer real potential for addressing the challenges of TSW in settings like Bangladesh and beyond. The intention was not just to summarize published work, but to distill meaningful insights from the literature that could inform sustainable, inclusive, and adaptable waste management strategies for the leather industry.

3 Existing TSW management techniques

TSW treatment has evolved from simple disposal to resource recovery. Early methods (1960s–1980s) such as landfilling and open dumping, reduced waste volume but caused long-term environmental pollution. Growing awareness of chromium toxicity led to second-generation technologies (1990s–2000s), including incineration and chemical hydrolysis, which enabled partial chromium recovery but raised concerns over air emissions, Cr^{6+} formation, and high operating costs, as illustrated in Fig. 3. Third-generation technologies (2010s–present) emerged from the convergence of circular economy principles and advances in process engineering. Current research focuses on integrated TSWM systems that sequentially produce biodiesel, biogas, biochar, collagen, and recovered chromium while optimizing leather production Fig. 3. The evolutionary trajectory demonstrates that no single technology answers all concerns; rather, optimal solutions depend on waste composition, cost, market demand, and regulatory frameworks.

Therefore, a comprehensive understanding of the evolutionary trajectory from the first generation onward is essential for developing integrated processes for sustainable TSW management. The management of TSW begins with landfilling, which remains the most widely practiced method due to its simplicity of operation, low cost, and rapid implementation.[36] However, landfill disposal of TSW has become an environmental and public health concern because of open dumps and the generation of leachate with high concentrations of heavy metals, which is regarded as aesthetically unpleasant, unsafe, and unhealthy.[37] The environmental impacts are coupled with landfill disposal because of the difficulty in site scouting, building, and operating modern landfills.[37,38] The leachate of CTSW comprises excessive quantities of hazardous metals and non-metals, predominantly Cr^{3+}, Pb^{2+}, and Cd^{2+} which pollute both ground and surface water along with soil. Landfill gas emission causes noxious circumstances, objectionable foul odor, foggy air, severe health effects, explosive mixture, and global warming.[37] Overall, direct landfilling of TSW is hazardous as well as inefficient, as precious CP and hazardous Cr(III) are being released into the environment.[20,39,40] Therefore, the ecologically safe disposal of TSW containing Cr has attracted scientific attention, and the route after landfilling arrives with immense possibilities is incineration.[41–43]

Incineration is a thermal waste management technique in which solid waste is completely oxidized at elevated temperatures ranging from 850–1200 °C in an oxidizing environment.[44] The disposal of TSW *via* the thermal incineration technique is

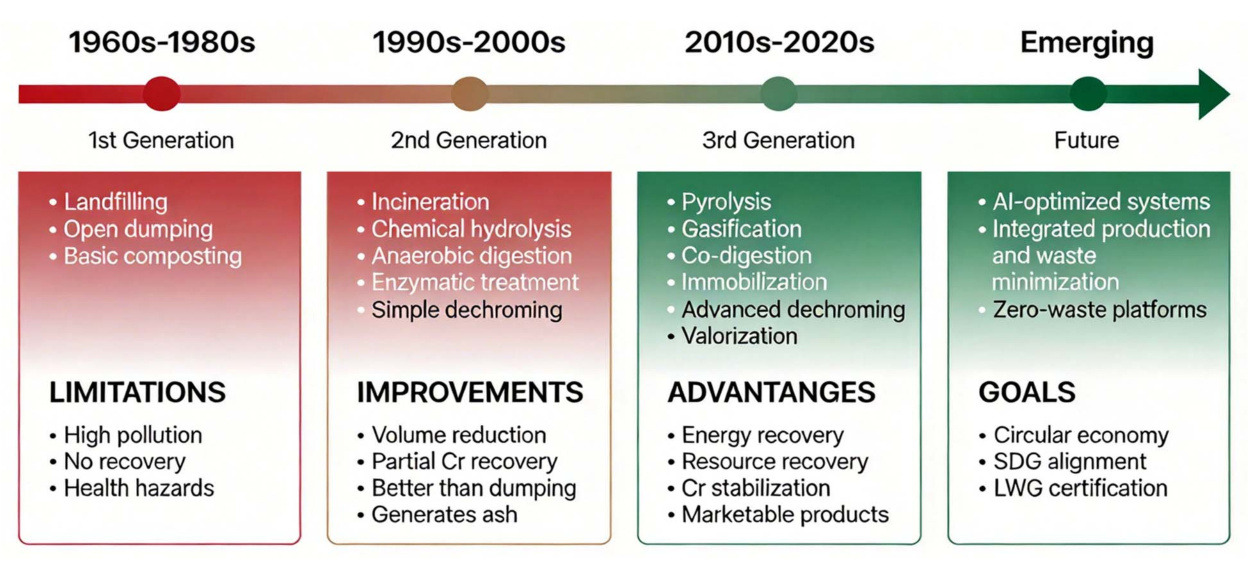

Fig. 3 Evaluation of TSWM approaches.

regarded as the cheapest and most attractive alternative to landfilling.[74] It has significant advantages over direct landfilling, including (a) reduction of organic content of the solid waste, (b) destruction of pathogenic microorganisms responsible for adverse health impact, (c) Cr recovery or solidification through the vitrification method, and (d) energy recovery from the resulting heat of the process.[39,45–47] However, a continuous supply of waste with minimal moisture content (MC) and high calorific value (CV) (>6 MJ kg^{-1}) is indispensable for this process, as high MC is shown to abate the efficiency of the incineration process by diminishing the reactor temperature.[43,48] Nonetheless, the thermal incineration of CTSW attracts special attention to prevent the release of hazardous substances, including polyaromatic hydrocarbons, halogenated organic compounds, and toxic Cr^{6+} into the environment.[41] Due to several constraints of the conventional incineration of CTSW, researchers were forced to design an updated approach for the thermal management of CTSW.

An upgraded route of incineration using fluidized bed combustion (FBC), or starved air incinerator (SAI) technology, was proposed to amend the operational efficiency of the incineration process.[41,49–51] Bahillo *et al.* (2004) employed a 0.1 MW bubbling fluidized bed pilot plant to study the efficiency of FBC for recovering energy from the incineration of footwear leather wastes. The investigation found no alteration of Cr^{3+}, and no Cr^{6+} was observed in the residue.[49] Swarnalatha *et al.* (2008) studied low-temperature (800 °C) SAI incineration operated at limited oxygen supply to recover energy and Cr from BD. Thus, the incineration of CTSW employing low temperature (≤800 °C) SAI or FBC technology has been seen to be a viable solution for the thermal management of CTSW. However, both processes produced substantial quantities of bottom ash that contain toxic heavy metals, primarily Cr^{3+} (about 50.2 mg g^{-1} of ash), with partially burnt carbon.[41,49] Swarnalatha *et al.* (2008) solidified Cr^{3+} containing ash as a low-cost perforated cement block using Portland cement and fine aggregates, which exhibits excellent Cr fixation of about 99.99% in the block.[41] Several studies reported that the Cr content in the ash can be retrieved[52] and utilized as raw material in the metallurgical/chemical industries to produce carbon-rich ferrochrome alloy, sodium chromate, basic chromium sulfate, *etc.* and recycled in the tannery itself.[43,53] Therefore, modified thermal incineration of TSW is more environmentally friendly compared to direct landfilling and incineration as it ensures effective recovery of Cr and energy, and minimizes secondary contaminants along with fewer residual remnants.[54] In addition, several latest reactors such as plasma cracking linked gasification–melting–vitrification and plasma pyro-gasification reactors are being used to produce bio-oil, syngas, and heavy metals valorization respectively from TSW.[55–57] In these approaches, the chromium ends up mainly as Cr(III) oxides or non-toxic ferrochrome locked inside the vitrified slag that can be valorized as raw material in the metallurgical industry or recovered back into the tanning process as chromium sulfate. Torrefaction is another modern method for TSWM approaches, where pyrolysis is done at lower temperatures (200–300 °C), resulting in bio-rich char, which could effectively be used in soil remediation and water treatment. During torrefaction, chromium remains predominantly in the bottom ash as Cr(III), while a smaller amount appears in the char in a more stable form, thereby reducing environmental risk and ensuring safer disposal of the char.[58]

Chemical methods like chemical oxidation, acid or base hydrolysis and enzymatic dechroming of CTSW have been conducted effectively. Oxidation techniques using strong oxidizing agents (*e.g.*, Cl_2, H_2O_2, and O_3) in a mildly alkaline environment (*e.g.*, Na_2CO_3 or $NaHCO_3$) are used industrially to recover Cr and other value-added products.[13,59,60] Investigation of the *in situ* generation of peroxochromates in the oxidation of CTSW in an alkaline environment reveals that peroxochromates have a great impact on the partial hydrolysis of collagen, which facilitates the isolation of gelatin.[13] The advantage of oxidation is that it is rapid and able to produce highly pure CP. However, it has some drawbacks, including relatively low removal efficiency, higher operating costs, and the production of hazardous secondary pollutants.

In acid hydrolysis dechroming (AHD), Cr^{3+} in CTSW, linked to the CP, is detached and exchanged with acid molecules, replacing protons and forming highly soluble complex compounds.[11,18,61–63] Beltrán-Prieto *et al.* (2012) used H_2SO_4, HCl, and CH_3COOH acid solutions for the dechroming of CS, and improved Cr was achieved by treating with a 5–10% H_2SO_4 solution at a temperature range of 333–343 K.[61] Extended reaction temperature, acid strength, and operation time have been shown to improve the extraction efficiency of Cr.[18] However, the potential issues of corrosion from strong acid and destruction of the original collagen structure due to hydrolysis of collagen, resulting in small polypeptide molecules, cannot be ignored.

Alkaline hydrolysis dechroming (ALHD) using CaO, MgO, $Ca(OH)_2$, NaOH, *etc.*, and basic organic compounds (*e.g.*, isopropylamine, diisopropylamine, cyclohexylamine, diisopropylamine) offers Cr^{3+} ion that dissociates effectively from CP and precipitates as chromium hydroxide $Cr(OH)_3$.[64–67] Su *et al.* (2008) recovered the collagen with a high extraction efficiency (88.98%) after pretreating the CTSW with NaOH at 120 °C for 4 h.[68] Therefore, ALHD of CTSW is comparatively more effective than AHD as it is easier to separate Cr as insoluble $Cr(OH)_3$ from the reaction mixture.

Enzymatic hydrolysis dechroming (EHD) processes use protease, trypsin, pepsin, Alcalase, *etc.*[65] enzymes to separate CP and Cr.[69] Pepsin was a gentle enzyme that controlled leather wastes, trypsin produced more and separated gelatin, which is of quite top-notch quality and cheap. The biological enzymes are activated at low temperatures in an alkaline environment within a shorter period and separate Cr as Cr^{3+} and CP as collagen hydrolysate, which has potential use in farming as NPK fertilizer.[12] It has been reported that the lower pH is undesirable as it could lead to the dissolution of Cr.[65] Improving the economic feasibility of EHD processes is feasible by lowering the enzyme concentration and separating gelable proteins, as the cost of the EHD process depends on enzyme concentration. Yet, the reaction rate also relies on it.

Combined hydrolysis dechroming (CHD) achieves significant recovery of Cr (>90%) and gelatin.[9] Chromium was initially removed by an acid–alkali or enzyme–acid/alkaline hydrolysis, and the residual chromium was removed *via* a bio-enzymatic approach.[70] However, the approach was limited by the elevated ash content in the extracted collagen protein hydrolysate (CPH).[13] Therefore, the approach was modified by maintaining alkaline conditions with low-molecular-weight amines, in combination with a reduced amount of inorganic base (*e.g.*, alkali and alkaline earth hydroxides, MgO). The modified enzymatic alkaline hydrolysis was successfully implemented in industrial production, yielding 80% CPH with minimal ash content. The blue section of Fig. 3 demonstrates the development scenario of the indirect chemical treatment technologies of CTSW.

The above treatment methods are mainly encountered in secondary pollution, lack of extraction efficiency, and high operational costs, which trigger the scientific community to explore considerably more sustainable solutions. Over the past century, several advanced sustainable technologies in biological, chemical, thermal, and immobilization solid waste management have been developed, as illustrated in Table 1.

The biological method refers to the aerobic, anaerobic microbial decomposition, digestion, detoxification, and earthworm decomposition of TSW to reduce waste volume, emissions, and toxicity, and recover resources.[38] Composting, co-composting, vermicomposting, aerobic and anaerobic digestion, co-digestion, and bioremediation are the recently developed biological methods for TSW management, as shown in Table 1. The biodegradation of TSW by microorganisms and enzymes is a widely used green-cleaning technology that helps mitigate the adverse effects of tannery waste. Many studies have been attempted worldwide to reduce the volume of TSW using enzymatic treatments. To biodegrade keratin wastes from the liming process, a keratinolytic yeast, *Trichosporon loubieri* RC-S6, was isolated from Cr-contaminated tannery waste soil and used for this purpose.

Composting nitrogen-rich TSW is a cost-effective and environmentally friendly method that yields compost with pH and heavy metal levels suitable for soil and plants.[71] Application of tannery sludge (TS) and agricultural waste-derived compost to ornamental peppers significantly increases leaf and fruit counts and chlorophyll content.[72] However, TSW's heavy metal content restricts its direct use owing to toxic effects on microbes involved in organic waste maturation and harmful bacterial elimination.[73] The co-composting of TS with domestic or agricultural waste lowers heavy metals in the compost and increases nutrient content.[74] Again, vermicomposting has huge potential to stabilize organic waste into a nutrient-rich substance[75,76] called vermicompost, a finely ground organic compound often used as fertilizer to re-incorporate biological material into soil.[77] Like composting, pristine TSW is toxic to earthworms; therefore, organic waste is mixed in varying proportions. The *E. fetida*[78] and *Eudrilus eugeniae*[79] earthworms transform TSW into vermicompost with higher NPK content, lower C : N ratio, and reduced electrical conductivity. Along with fertilizer production, energy recovery *via* anaerobic digestion (AD) has been popularly practiced due to the high organic content of TSW.[80,81] Studies reported moderate CH_4 production (0.596 m^3 kg^{-1}) with higher volatile suspended solid material removal (71%) in the AD of several TSWs, including fleshings, skin trimmings, and TS.[82] Recent studies have found that the addition of enzymes could improve the efficiency of digestion.[83] The sulfide content of lime fleshing increases H_2S content in biogas, which reduces methane generation.[84] The anaerobic co-digestion of TSW with biodegradable waste has been shown to yield a higher quantity of biogas (about 74–81%)[85] and microbial biomass with high nitrogen content, carbon–nitrogen ratio (20–30 : 1), and decreased Cr content.[86] However, before taking action against improper management of hazardous TSW, it has already poisoned the soil with heavy metals, mainly Cr^{6+}. Apart from several other bacteria, including *Brevibacterium luteolum* (MTCC-5982),[144] *Aspergillus carbonarius*,[89] *Bacillus subtilis* (P13),[145] *A. thioxidans*,[146] and *Acidithiobacillus thiooxidans* (TS6),[147] show better Cr^{6+} resistance both in contaminated soil and TSW with greater detoxification efficiency.

Thermal oxidation processes are suitable for waste with high organic content and low MC. Studies reported that TSW has moderate-higher heating value (HHV) (12.5–21 MJ kg^{-1}), high carbon (5–26%) and volatile content (>60%), with low moisture (5–15%) and ash content (<10%). These thermochemical properties of TSW make it suitable for thermal treatment to recover energy.[34,87] Combustion is an attractive way to recover energy, although moderate HHV and considerably high ash and volatile content of TSW are a source of concern. Apart from high-temperature combustion, this is connected to the emission of higher concentrations of NO_x and CO_2, and produces hazardous Cr^{6+} in bottom ash.[26,34] Co-combustion of this waste with biomass, coal, or various TSW can open up the way to recover energy by effectively reducing the volatile and ash content.[88,89] Hardwood pellets (HP), a renewable energy source, show a similar maximum average temperature (750–850 °C) in co-combustion with TSW. Studies reported that the ash and volatile content of TSW were reduced to a considerable amount in co-combustion with HP. However, the co-combustion of TSW with HP emits twice as much NO_x as the combustion of HP.[90] Similarly, TS and bituminous co-combustion yields also enhanced Cr content in leachate and fly ash.[88] Char reduction technology has been shown to reduce NO_x emissions and decouple at higher gas flow rates; combustion could cut even more.[91] Decoupling combustion (DC) is a two-step combustion process in which fuel pyrolysis and the combustion of char occur simultaneously, pyrolysis gas is separated and burned out during its transit through the burning char bed. The DC of TS, chrome shaving (CS), and chrome buffing dust (BD) show enhanced co-combustion behavior (*e.g.*, raised comprehensive combustibility index, flammability index, and stable combustion characteristic index). Gasification is another thermal method that converts biomass into gaseous fuel in the presence of a regulated quantity of air, steam, or oxygen, known as the gasifying medium.[92,93] Recent studies reported that the gasification of biodegradable TSW in downdraft gasifiers produces a gaseous mixture of H_2, CO_2, CO, C_2H_2, and C_2H_6. It is stated that combustible gases are generated in substantial quantities, ranging from 29% to 33% of total gas production, with the remainder being non-combustible.[94] Nevertheless, this process

Table 1 Recently developed technologies for the sustainable management of TSW

Types of treatment	Treatment approach	Followed by	Name of products	Reference
Biological	Composting	—	Organic fertilizer	109–111
	Vermicomposting	—	Organic fertilizer	112–115
	Anaerobic digestion	—	Biogas	82 and 116–119
	Anaerobic co-digestion	—	Biogas (bio-hydrogen)	85 and 120–125
	Bioremediation	—	Convert Cr(VI) to Cr(III)	126–128
	Biodegradation	—	Degrade TSW	129 and 130
	Phytoremediation	Phytostabilization, phytoextraction, phytostimulation, phytofiltration, phytotransformation	Improve heavy metal-contaminated soil	131
	Bioleaching	—	Recovered Cr	132–137
	Biodegradation	Hydrolysis with protease, amylase, and filtration	High-purity protein hydrolysate	138
Chemical	Acid hydrolysis	Degumming & saponification	Fat, soap	139
		Acid pretreatment and transesterification	Fat, biodiesel, and paraffin production	140–144
	Alkali hydrolysis	Precipitation of chrome liquor	Fat, biodiesel	143
	Dechroming	Alkali, oxidation, and thermal treatment	Cr–gelatin protein/collagen protein	145 and 146
	Chemical composite/blending	Mixing leather fiber with natural fiber	Biodegradable packaging films, composite materials, and composite sheets	147
	Enzymatic hydrolysis	Acid pretreatment and transesterification	Biodiesel	148 and 149
	Alkali–acid hydrolysis	Transesterification	Fat, biodiesel	150
		Soxhlet extraction and transesterification	Fat, biodiesel	151
	Soxhlet extraction	Degumming and saponification	Fat, soap	152
		Degumming and transesterification	Fat, biodiesel	141
Biochemical conversion	Enzymatic decomposition	Fermentation	Methane gas, alcohol	153
	Nanobiodegradation	Endocytosis and intercellular degradation	Biopolymer	154
	Phytoremediation	Allow to grow in tannery sludge	Bioaccumulated heavy metals on the trees from TSW	155
Thermal	Co-combustion		Energy	26, 88, 89, 91, 128 and 156
	Pre-carbonization	Chemical activation	Supercapacitors	157
	Calcination		Biomass briquettes	158
	Gasification		Synthesis gas	159
	Pyro-gasification	Acid leaching, fractional precipitation, and neutralization by NaOH	Cd, Pb, and 96.3% of Zn	160
	Pyrolysis	H_3PO_4 activation	Bio-oil, biochar, tar	161–166
	Thermo-chemical	CaO-embedded in activated carbon	Fillers in rubber soles	161
		Chemical treatment after thermal treatment	Moisturizers and cosmetics	3
Immobilization	Collagen/gelatin extraction	Composite production *via* different methods (*e.g.*, stir casting, share milling)	Composite materials (*e.g.*, MMCs, CF/TPU, bio-composite)	97, 99–102 and 167
	Incorporation of hazardous TSW by mechanical process		Brick, ceramics, TSW-coated asphalt, acoustic panels, and green building materials	168–173
	Vitrification		Glass matrix	174

has flexible operating conditions and it prevents the oxidation of Cr^{3+} to Cr^{6+}.[26] Di Lauro *et al.* (2022) gasified TS with Cr^{6+} below 2 ppm in a lab-scale FBR at 850 °C and produced gaseous fuel with a lower heating value of 12.0 MJ Nm^{-3}.[10,95] Recently, the pyro-gasification of TSW at elevated temperatures (about 1500 °C) has attracted attention for heavy metal recovery. Demand for renewable energy and waste disposal issues boosted biomass briquette manufacture. The briquetting of leather fleshing (LF), lime fleshing, shaving, polishing, and clipping solid waste samples resulted in highly durable (about 97.83–99.54%) briquettes with higher heating value (also called gross calorific value) (HHV) (19.82–21.86 MJ kg^{-1}) with superior compressive strength (about 0.17–0.21 kN cm^{-2}) that fulfilled the minimum briquetting densities of 600 kg m^{-3}. Thus, converting TSW to briquettes for fuel would solve the disposal issues of TSW and give an alternative to fossil fuel.[96]

In terms of TSWM, immobilization corresponds to the method of stabilizing hazardous chemicals (*e.g.*, heavy metals, toxic chemicals) inside a closed matrix by manufacturing various products such as ceramic, glass, acoustic panels, green building materials, composite materials,[97–102] cement, and so on, as shown in Table 1. Immobilization prevents these hazardous materials from leaching into the ecosystem and causes adverse ecological and health impacts.[103] Various components extracted from TSW can be used as composite-making material.[97,98] The collagen powder extracted from leather waste has high tensile strength.[98] It is employed as a reinforcing material with Al_2O_3 to produce metal matrix composites (MMCs) with high tensile strength, compact strength, and hardness.[98] MMCs find use in applications where weight savings are critical (*e.g.*, robots, high-speed equipment and rotating shafts, ships, broken components, and automobile engines).[104] The application of 50% collagen powder to produce collagen fiber-thermal polyurethane elastomer (CF/TPU) gives higher tensile strength and elongation.[101] The immobilization of chromium-tanned leather fragments in the asphalt surface resulted in less cracking.[105] TS combined with clay can be utilized for producing ceramic materials like bricks within the matrix in which Cr gets immobilized.[106] Reinforced bio-composites made from leather shavings and cement have high mechanical characteristics and may be used in the construction sector.[107] Juel *et al.* (2017) developed a clay brick with varying concentrations of TS and found its suitability as a building material. The bulk density panels produced from TSW (*e.g.*, BD, CS) in combination with sawdust show excellent insulating properties in computer simulations of insulated buildings.[31] Therefore, this kind of panel is observed to be economically competitive with other materials like polystyrene, according to an examination of thermal comfort and energy use. The investigation revealed that more than half of the energy consumption in a year was reduced by using a 7.5 cm-thick coating of BD. Therefore, it can be concluded that the treatment of TSW provides value for novel immobilized materials without the need for any further processing.[108]

4 TSW valorization techniques implemented by companies worldwide

Already, a significant number of companies from different parts of the world have started sustainably commercializing tannery solid, as illustrated in Table 2. The recovery of Cr, fat, collagen protein, and the synthesis of value-added products from chemical treatments are necessary. Biodiesel manufacturing by the transesterification of recovered fat presents a viable option for the sustainable management of TSW.[148–154] Soxhlet extraction of fat from TSW with high extraction efficiency (about 90–98%) has been popularly used, ignoring its high energy consumption and requirement of hazardous chemicals.[150,152,153,158] Fat extracted from TSW, especially leather fleshings, has high free fatty acid (FFA) content (about 40%) that needs acid pretreatment before transesterification.[153,159] A recent study reported that only 6.2 kg of LF can produce 1 L of biodiesel that meets the requirements of EN-14214.[153,163] Apart from saponification of extracted fat with about 20% NaOH solution is another chemical method for sustainable TSW management that yields soap with good lathering and cleansing power.[150,166]

Gil *et al.* (2016) prepared a slow-release drug for wound and burn healing that eliminates the need for dressing changes, employing Cr-free collagen protein from TSW and replacing it with the antibiotic silver sulfadiazine. TSW may also be utilized as an appropriate raw material for the synthesis of industrially significant products. The Indian Council of Scientific and Industrial Research (CSIR) and the Central Leather Research Institute (CLRI) took the initiative to treat two tons of TSW in a day to produce biofuel. From each ton of TSW 200 litter biodiesel, 200 Liters of bioethanol, 120 m^3 of bio-hydrogen, and 200 m^3 of methane have been produced.[175] CSIR and CLRI in Kolkata, in a joint effort, built a TSW management pilot plant to produce biogas through the co-digestion of 0.75 tons of TSW per day. However, it is not sufficient to manage the total amount of TSW produced by the Calcutta Leather Complex and other tanneries. CSIR-CLRI jointly established a high-quality gelatin production plant in Chennai; an activated carbon production plant using TSW to produce shoe soles or tires; and an asphalt production plant for road construction in Chennai and Delhi. CLRI independently established a plant in Chennai to produce corneal implants, bone grafts, collagen sponges, collagen film, keratin films, bandages, and dog chews from TSW (Table 2).[176] EU, in collaboration with Solidaridad Regional Expertise Centre, Politecnico Internazionale per lo Sviluppo Industriale ed Economico (PISIE), Indian Finished Leather Manufacturers and Exporters Association (IFLMEA), Council for Leather Exports, and Tata International Limited initiated a plant in Tamil Nadu, India for converting semi-finished leather into finished and value-added products for export.[177] BLC Leather Technology Center Ltd and Biomass Engineering, a British company, set up a gasification pilot plant to produce energy from TSW. The capacity of this pilot plant was 75 kg of TSW per hour, capable of treating 24 tons of TSW per day.[178] Scottish Leather Group (SLG), the largest bovine leather manufacturer in the United Kingdom (UK), has established a fully commissioned Thermal Energy Plant (TEP) costing $9 M at its Bridge of Weir site near Glasgow. SLG has a diverse range of interior and transportation suppliers, including Bridge of Weir Leather, Andrew Muirhead & Son, NCT Leather, and W J & W Lang. The TEP will produce 45 kWh per year from 30 000 tons of waste generated by the group's subsidiaries.[179] Italian company ILSA began operations in Brazil in 2009 and has converted over 300 000 tons of leather waste into fertilizers.[180] Bertin, a Brazilian consortium of agroindustry, launched their first biodiesel plant in Lins, São Paulo state. The $21 M USD biofuel facility has the world's greatest installed capacity and uses bovine tallow as raw material from the company's slaughterhouse and tanning procedures. The plant has the capacity to yield 110 million gallons of biodiesel annually and can also adapt to convert vegetable oils.[181] An American company, Beef Products Inc. (BPI), has partnered with Natural Innovative Renewable Energy to build a 60 million gallon per year biodiesel facility in South Sioux City, Nebraska. The primary source of feedstock for biodiesel production is BPI's beef tallow. Once the factory achieves its maximum capacity, it is anticipated that other meatpacking companies will provide additional feedstock, and the facility will annually produce around 55 million pounds of glycerin.[182] Dongming Bright Cattle Co. Ltd, located in Hebei province in northern China, annually recycled about 600 tons of shaved hair as organic fertilizer.[183] In Bangladesh, Anjuman

Table 2 A review of recycling and valorization techniques for TSW employed by companies in different countries

Country	Company or organization	Valorization approach	Capacity and cost	Revenue/production/outcome	References
Bangladesh	Anjuman Trading Corporation Ltd	Export STIE tannery solid waste to Cambodia	200 tons per month	\$300 per ton	184
	Resources Regeneration BD Ltd. in collaboration with ILSA	Bio-fertilizer, electricity	—	Project fails	185
India	The Central Leather Research Institute (CLRI), Ranipet, Chennai	Bio-fuel production	2 tons per day. Pilot plant cost: \$12.8 M USD	200 L biodiesel, 200 L bio-ethanol, 120 m^3 bio-hydrogen, 4.200 m^3 methane per ton of TSW	175
	CSIR-CMERI and M/S Basudev Biodiesel LLP, Bhubaneswar, Odisha	Biodiesel			186
	CSIR-CLRI, Chennai	High-quality gelatin	50 kg of trimmings per ton of raw hides	10 kg gelatins/50 kg trimmings	187
	CLRI, Chennai	Corneal implants, bone graft, collagen sponge, collagen film, keratin films, bandages, dog chews	—	—	176
	EU and Tamil Nadu, India in collaboration with five major companies	Semi-finished leather into finished and value-added products for export	42 month initiative	—	177
UK	BLC Leather Technology Center Ltd and Biomass Engineering	Gasification plant to produce energy	Pilot plant: 75 kg h^{-1}. Full-scale plant: 24 tons per day	1 kW h^{-1} of energy per 1 kg of waste	178
	Scottish Leather Group (SLG), Scotland	Thermal Energy Plant (TEP), Glasgow	30 000 tons of waste per year. Plant cost: \$9 M USD	45 million kW per year	179
Brazil	Bertin Group, Lins, Sao Paulo state	Biodiesel	\$21 M USD	110 million liters of biodiesel per year	181
	ILSA	Bio-fertilizer by thermal hydrolysis process	—	300 000 tons of fertilizer by May 2021	180
United States	Beef Products Inc. (BPI), South Sioux City, Nebraska	Biodiesel, glycerin	—	60 million gallons of biodiesel per year and 55 million pounds of glycerin per year	182
China	Dongming Bright Cattle Co. Ltd, North China, Hebei	Organic fertilizer	600 kg of hair is treated as organic fertilizer		183

Trading Corporation Ltd initiated a contract with the Savar Tannery Industrial Estate (STIE) authority to export STIE's TSW to Cambodia. For each ton of TSW, Cambodia will pay 300 USD.[184] Resources Regeneration BD Ltd signed a contract with an Italian company, ILSA, to establish a company in Saver, Gazipur, Bangladesh, for producing bio-fertilizers and energy; however, the project failed.[185] Several other companies across the world attempt to commercialize solid tannery waste in addition to the businesses and organizations indicated in Table 2. Organizations and enterprises involved in leather production could undertake the challenge of creating an inclusive platform for companies to commercialize TSW for future research and innovation.

5 Sustainability of TSW

5.1. Proposed model of TSWM for developing nations

Although several companies worldwide have implemented various commercialization strategies for TSW, a substantial proportion of this waste stream remains inadequately treated, resulting in the continued loss of valuable resources and persistent environmental burdens. Circular economy model is considered to be a potential solution as it utilizes less energy and renewable resources, recycles waste to the maximum feasible extent, and ensures reduced environmental emissions. Note that, the second law of thermodynamics states that in any energy conversion, entropy increases, thus some energy is being lost usually as heat. Therefore, materials and energy cannot be perfectly cycled without losses or degradation. Every process results in energy dissipation and reduced material quality, requiring additional energy input to maintain the cycle.

Therefore, the application of the circular model may improve business growth by using advanced technology and enhancing enterprise goodwill. In tannery industry, it includes recycling, component repair, and upgrading, as well as the use of renewable resources such as secondary raw materials from TSW.[183,188–191] Considering the aforementioned, a circular economy model for the tannery industry can be established through the integration of effective eco-benign TSWM technologies, as depicted in Fig. 4. Nevertheless, the model is purely conceptual and provides a platform for future research, which will cover the development of pilot-scale models, evaluation of energy efficiency, sustainability assessment, and other key assessments that are likely to establish an effective circular economy model for TSWM.

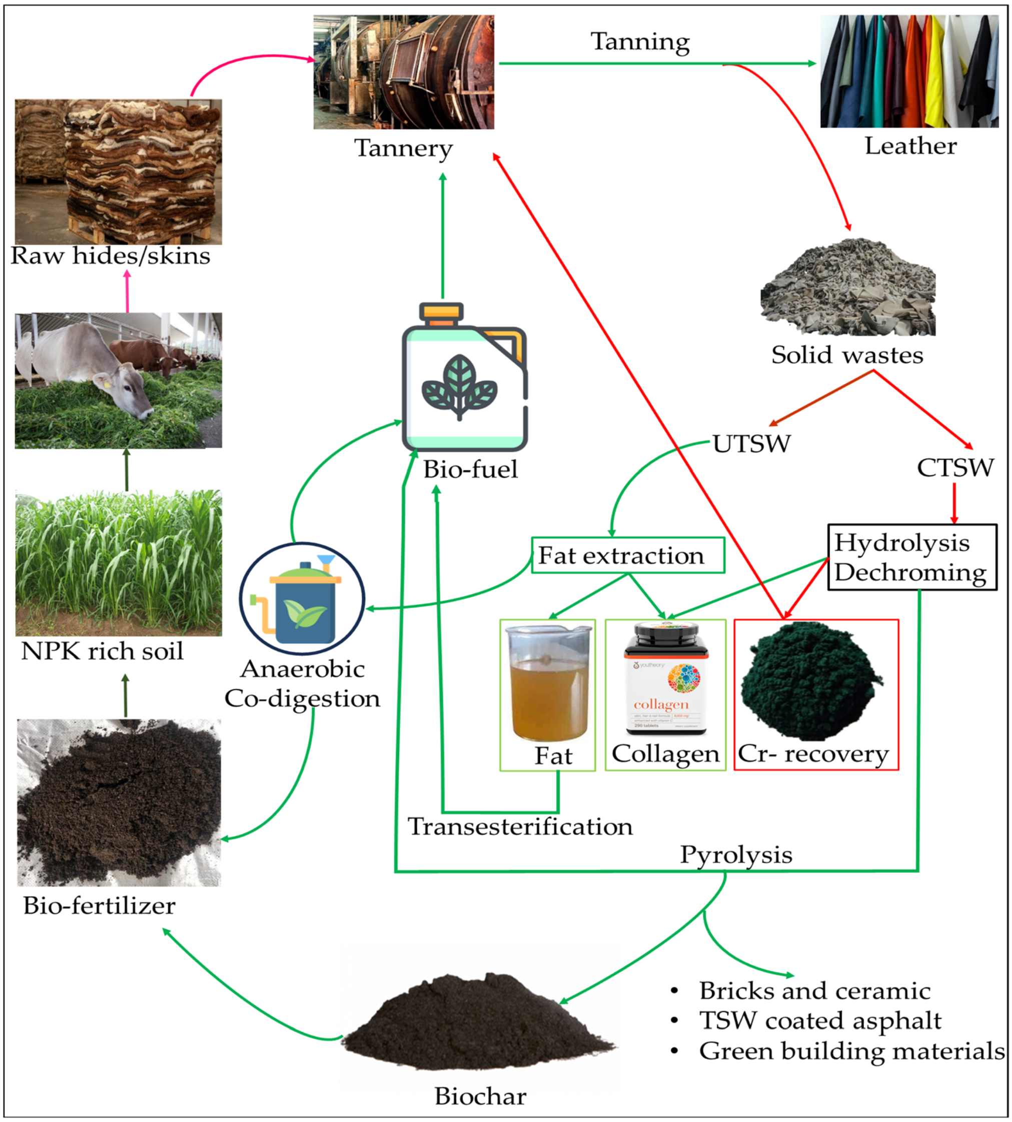

Fig. 4 Proposed CE model of tannery solid waste management (TSWM).

CTSW and untanned solid waste (UTSW) comprise valuable proteinaceous substances, including fat (3–6%), minerals (15%), and CP (90%), while CTSW contains hazardous Cr_2O_3 (3.5–4.5%).[64,192–195] Therefore, CTSW can be fed into a combined hydrolysis dechroming unit to recover hazardous Cr and valuable collagen protein.[64,192–195] A recent study concluded that the conversion of TSW to energy is the most appropriate valorization technique as it addresses the issue of carbon emissions, and solid waste management and explores renewable energy.[196] Therefore, the remnants from the hydrolyzer can be pyrolyzed or co-pyrolyzed in a fluidized bed reactor (FBR) or fixed-bed reactor at low temperatures to produce high-quality bio-oil, syn-gas, and biochar[43,165,166] as illustrated in Fig. 4. The UTSW, especially leather fleshings, can be separately treated to extract fat *via* the Soxhlet extraction method or alkaline hydrolysis for producing biodiesel. To produce biodiesel, the extracted fat with high FFA content is transesterified after acid pretreatment.[141,143] The effluent after transesterification, along with other UTSW, can be alkaline/acid–enzyme hydrolyzed to extract collagen protein.[43,165,166]

After that, the remnants can be fed to an anaerobic digestion plant with organic waste to produce biogas.[120–125] The sludge from anaerobic digestion can be directly composted/vermicomposted or directly used as a bio-fertilizer.[109–111,197] TSW with hazardous chemicals (*e.g.*, heavy metals, toxic chemicals) can be immobilized by producing bricks, ceramics, and cement.[168–173] The recovered Cr can be converted to basic Cr(III) sulfate by reacting with $Na_2S_2O_3$, and recycled back to the tanning operation.[43,53,198] Alongside, the extracted collagen protein can be utilized to produce various composite materials, gelatin, and find value as a raw material for food, pharmaceuticals, and cosmetic industries.[97–102,195] Recovered bio-oil, syn-gas, biodiesel, and biogas can be reused as secondary energy sources for the highly energy-consuming tanning process. Biochar can be used as an adsorbent for tannery wastewater treatment. Apart from that, compost and biochar can be used as

Fig. 5 Optimized TSWM supports achieving the SDGs.

fertilizer to reincorporate the nutrients and organic content into the agricultural soil that produces plants for cattle.

Several developing countries is now producing huge sum of hazardous and valuable TSW (such as Bangladesh produce 82 million kg annually). However, most of them are landfilled or incinerated as these nations faced the shortcomings of collaborations with different organizations due to a lack of long-term policies, initiatives, and economic constraints. Inadequate research and development (R&D) and skilled manpower hinder these nations from achieving its desired goals in the TSWM of the leather and allied industry.

Implementing circular economy (CE) methods in the leather sector could be facilitated by the combination of green architecture, IoT, AI, blockchain, and LCA as they build an effective, data-driven system for tannery waste management by lowering resource consumption, enhancing waste monitoring and processing, ensuring transparency, and promoting sustainable decision-making.[199]

5.2. Achievable SDGs for TSWM

This study highlighted multiple SDGs by addressing the health and environmental risks of tannery solid waste (TSW), especially chromium pollution, contributing to SDG 3 (health) and SDG 6 (clean water) through improved waste management and reduced hazardous discharge. Valorization of TSW into bioenergy (*e.g.*, biodiesel, biohydrogen, and biogas) aligns with SDG 7 (clean energy) by utilizing TSW. Implementing proper TSWM and the proposed CE in the leather industry will promote economic growth and job generation through sustainable practices and LWG certification (SDG 8), while encouraging innovation in the leather sector (SDG 9) and responsible production (SDG 12). Sustainable TSW management helps reduce greenhouse gas emissions (SDG 13), limits water pollution (SDG 14), and protects ecosystems and biodiversity (SDG 15) (Fig. 5).

To improve TSW treatment efficiency, lowering costs, and lessen the environmental effect, future research should emphasize optimizing the integration of novel approaches with traditional methods. As demonstrated by earlier research, integrating new technology with conventional techniques can result in notable changes in total TSWM.

5.3. Social indicators of sustainable tannery solid waste management

Sustainable TSWM in Bangladesh requires addressing key social issues, including health risks to workers and nearby communities,[200] economic impacts such as livelihood loss[201] and displacement,[202] and social stigma related[203] to tannery waste. These challenges can be mitigated through awareness programs, inclusive decision-making involving local communities and institutions, and continuous information sharing. Ensuring fair distribution of benefits among all social groups, especially marginalized populations, is essential for achieving socially sustainable waste management.[204] Accomplishment of identical favorability from solid waste management projects or industry to women, the poor, marginalized groups, physically challenged individuals, and remote and minor communities would possibly be the foremost ways to avoid these challenges.[205,206]

6 Conclusions

Over the past six decades, global TSW generation has increased by more than 100-fold, yet data remains fragmented, hindering informed policymaking and strategic implementation of sustainable technologies. Key advancements highlighted include the valorization of TSW through biodiesel and soap production from fat-rich fractions, which offers direct compatibility with existing energy systems and consumer products. Enzyme-mediated anaerobic co-digestion has emerged as a viable route to enhance biogas yield and mitigate methane losses. Low-temperature fluidized bed gasification and decoupling co-combustion represent innovative energy recovery solutions that minimize harmful Cr^{6+} emissions. Pyrolysis and pyro-gasification technologies have shown promise for both energy generation and heavy metal recovery, while composting and vermicomposting, when paired with agricultural residues, can yield fertilizers with safe nutrient profiles. From a materials perspective, sustainable immobilization strategies, such as producing composite materials, bricks, and ceramics, can safely encapsulate hazardous components while generating economic value. Furthermore, emerging research on collagen valorization and pigment recovery suggests high-value applications in biomedical and industrial sectors. Despite these advances, widespread commercialization is limited by a lack of harmonized global data, insufficient policy support, and economic constraints in developing nations. Therefore, a unified international database, strong policy mechanisms (*e.g.*, Extended Producer Responsibility, carbon taxes), and reallocation of subsidies from fossil to biofuels are essential. Public engagement, strict regulation enforcement, and stakeholder inclusion are critical for avoiding indiscriminate disposal. Looking ahead, future research must prioritize LCA and TEA to validate environmental and financial viability. Collagen-based biomaterials, Cr-free tanning agents, and fertilizers from biogas plant residues represent promising avenues requiring commercial-scale validation. Ultimately, integrating circular economy principles into TSWM can bridge environmental, social, and economic sustainability, contributing to SDG compliance and facilitating broader LWG certification in the leather sector.

Author contributions

Debanjon Sarker: writing – original draft, visualization, data curation. Saidur Rahman Shakil: writing – original draft, formal analysis, data curation, methodology. Nazmul Huda: writing – original draft, methodology, validation. Hridoy Roy: writing – original draft, visualization, validation, conceptualization. Manjushree Chowdhury: writing – review & editing, conceptualization. Md. Shahinoor Islam: writing – review & editing, supervision, project administration, conceptualization.

Conflicts of interest

The authors declare no competing financial interests.

List of abbreviations

TSW	Tannery solid waste
SDG	Sustainable development goal
LCA	Life cycle assessment
TEA	Techno-economic analysis
CP	Collagen protein
LWG	Leather Working Group
CE	Circular economy
CTSW	Chrome-tanned solid waste
CT	Chrome tanning
CETP	Central effluent treatment plant
FAO	Food and Agricultural Organization
TSWM	Tannery solid waste management
NGOs	Non-governmental organization
MC	Moisture content
CV	Calorific value
FBC	Fluidized bed combustion
SAI	Starved air incinerator
AHD	Acid hydrolysis dechroming
ALHD	Alkaline hydrolysis dechroming
EHD	Enzymatic hydrolysis dechroming
CHD	Combined hydrolysis dechroming
NPK	Nitrogen–phosphorus–potassium
CPH	Collagen protein hydrolysate
TS	Tannery sludge
AD	Anaerobic digestion
HHV	Higher heating value
HP	Hardwood pellets
DC	Decoupling combustion
CS	Chrome shaving
BD	Chrome buffing dust
LF	Leather fleshing
MMCs	Metal matrix composites
CF/TPU	Collagen fiber-thermal polyurethane elastomer
FFA	Free fatty acid
CSIR	Council of Scientific and Industrial Research
CLRI	Central Leather Research Institute
PISIE	Politecnico Internazionale per lo Sviluppo Industriale ed Economico
IFLMEA	Indian Finished Leather Manufacturers and Exporters Association
SLG	Scottish Leather Group
TEP	Thermal energy plant
BPI	Beef Products Inc
STIE	Savar Tannery Industrial Estate
UTSW	Untanned solid waste
FBR	Fluidized bed reactor
IoT	Internet of things
WtE	Waste to energy

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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