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Thermal pathways for sustainable waste management: Leveraging leather tannery waste as a renewable energy source

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ABSTRACT

The growing production of consumer goods increases waste generation, challenging disposal systems. The aim of the work was to use real data to propose a closed loop leather production process, so as to eliminate storage and use the potential of thermal processes for energy recovery. Such actions allow for improving the company's economic balance, but above all for a positive environmental impact. The tanning industry generates about 825 kg of waste per 175 kg of finished leather, mostly landfilled at high costs of utilization. This study examines energy recovery from tannery waste in various path: combustion, pyrolysis, and gasification using data from a Polish tannery.

Results: show combustion has the highest energy yield (94 %), followed by gasification (75 %) and pyrolysis (43 %). The technological process was analyzed and the potential of the by-products generated was quantified. Offcuts offer the highest energy recovery potential, while tannery sludge is the largest waste mass. Energy-intensive processes such as TAIC, dyeing, and cutting require significant power, with offcuts and shaving waste demanding 66.9 kWel and 31.3 kWel, respectively. Thermal energy from incineration meets heating needs and supports waste drying, while waste heat in an Organic Rankine Cycle (ORC) covers 40 % of electricity demand.

This research highlights the benefits of shifting from landfill disposal to sustainable waste management, reducing costs and environmental impact. The proposed calculations demonstrating how engineering can enhance sustainability in the leather industry and others.

1. Introduction

The tannery industry has been established for centuries, yet managing the waste streams generated during the tanning process remains a significant challenge. This issue is particularly relevant in the context of sustainable development goals (SDGs), net-zero emissions targets, (Fankhauser et al., 2022) and the reduction of anthropogenic greenhouse gas (GHG) emissions. According to the Central Statistical Office (CSO) of Poland, the leather and leather products sector in Poland generated 55.1 thousand tons of waste in 2019. As the leather products industry is usually associated with luxury items, the tanning industry is a large part of the developing world's economy of goods, which is estimated at approximately 100 million dollars per year (UN-FAO, 2013). Effective management of waste and waste biomass, especially the large volumes produced by industry, is crucial, as these are often still sent to landfills. According to the waste hierarchy, material recycling takes precedence over energy recovery. In industrial processes, only a small portion of the total waste stream is recycled, making energy recovery an important complementary strategy. Current literature predominantly addresses laboratory-scale solutions and lacks practical applications for managing industrial-scale waste. Examples include proposals such as using fleshing waste as a fertilizer carrier (Skrzypczak et al., 2024, Skrzypczak et al., 2022), biodegradation techniques (Rigueto et al., 2020; Suresh et al., 2021), anaerobic digestion process (Tafirenyika and Manyuchi, 2018), collagen recovery (Asava et al., 2019), and its use as an additive in the production of other materials (Abioye et al., 2024).

The challenge of managing tannery waste for energy production on an industrial scale remains unresolved. In this study, various methods of thermal waste management were analyzed through a review of available

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Nomenclature

WW	wet white tanning process/waste
WB	wet blue tanning process/waste
HHV	higher heating value
RDF	refuse-derived fuel

research to develop feasible solutions for energy management of tannery waste in quantities generated by actual industrial processes. To date, only a few studies have addressed the utilization of tannery waste for energy production.

Wang et al. (2015) proposed an innovative solution for the management of tannery waste by suggesting the granulation of waste and its mixing with raw material blends, such as refuse-derived fuel (RDF), to enhance its energy recovery potential. By implementing this approach, tannery waste, which is characterized by low calorific value and poor autothermal properties, can be utilized in energy recovery processes.

Research on the application of pyrolysis for energy generation from tannery waste has predominantly focused on laboratory-scale studies. A key parameter determining product distribution and process feasibility is temperature. At temperatures below 450°C, a higher amount of solid waste is produced, with most of the present Cr^{III+} retained in the solid fraction. This is crucial, as increasing the process temperature above 600°C leads to the transformation of chromium into its toxic Cr^{VI+} form (Copik et al., 2023). In the study by Kluska et al. (2019), an increase in carbon content in the solid fraction was observed, making the resulting char a potential fuel. The higher ash content compared to other types of biomasses may pose challenges for the continuous operation of reactors on a larger scale (Kluska et al., 2019). An increase in pyrolysis temperature significantly reduces char yield in favour of gaseous products, decreasing from 87.5 % to 49.0 % within the temperature range of 200–800°C (Li et al., 2024). Onem et al. were used pyrolysis prosess for the production of oils, followed by the processing of these oils through gaseous phase cracking to obtain fuels (Onem et al. 2024). Another example is the roasting process (slow pyrolysis at 400°C in a nitrogen atmosphere) studied by Yuan et al. (2021), which resulted in the carbonization of leather waste. The produced char, used as a precursor for activated carbon, demonstrated high efficiency in removing heavy metals such as Cu, Co, Pb, and Ni from wastewater (Yuan et al., 2021). This example illustrates the broad potential applications of pyrolysis products in environmental quality improvement processes. Du et al. (2025) provide a comparative analysis of microwave pyrolysis and conventional pyrolysis of tannery sludge, finds that microwave pyrolysis facilitates the reduction of Cr^{VI+} to Cr^{III+} as well as helps to fix heavy metals in the residues.

Another promising method for the management of tannery waste is gasification, which exhibits certain exothermic properties. During this process, the conversion of carbon-containing materials into a combustible gas mixture occurs at temperatures typically exceeding 700°C under limited oxidant availability (Suryawanshi et al., 2023). Shahbaz et al. (2024) presents a theoretical model of steam gasification of tannery waste coupled with power generation, clearly showing the feasibility of energy recovery. This path has the potential to achieve net-zero carbon emissions while offering environmental and financial benefits by utilizing tannery waste for energy production. Fankhauser et al., (2022); Wang et al. (2015) conducted gasification in an updraft reactor at an equivalence ratio (ER) of 0.16, producing a gas with a calorific value of 4.4 MJ/Nm^3 (Wang et al., 2015). A higher calorific value of 6.7 MJ/Nm^3 was achieved at ER = 0.2. These results suggest that gasification can be an effective solution for the industrial-scale management of tannery waste. Noteworthy is production of briquettes for use in the energy sector (Hagos et al., 2023). A similar approach to waste management is briquettes produced in this case are made from non-thermally treated waste. In paper six briquettes, comprising varying ratios of hair, flesh, chrome shavings and buffing dust, were molded and characterized (Onukak et al., 2017). Thermal efficiency, durability and compressive strength, among other properties, were determined for the six briquette formulations. The high calorific value in the range of 17–24 Mj/kg gives them a good chance of being used as solid fuel. When reviewing the work of other researchers, it is important to pay attention to local conditions and the characteristics of the tanning industry. Depending on the region of the world, there is a prevalence of tanneries processing fresh hides, or of tanneries for tanning, where pre-tanned hides are subjected to leveling, waxing, clipping, etc. Depending on the type of process, there are different wastes. It is also worth noting the tanning technique. In Europe, there is a move away from wet blue technology, which is still the primary tanning technology in the rest of the world. The chromium in the leather can affect not only processes such as fermentation, but even processes such as burning or gasification.

An interesting alternative for the thermal degradation of leather waste is hydrothermal carbonization (Lee et al., 2019) though it has not yet been implemented on an industrial scale. This process, carried out at temperatures between 180 and 200°C, aims to produce hydrochar (Lang et al., 2018). The key advantage of hydrochar compared to biomass is its lower sulfur and nitrogen content, which reduces the amount of oxidative pollutants in exhaust gases during combustion. Experimental study on hydrochar (Peng et al., 2016) found that it exhibited improved fuel properties, including higher heating value (HHV) and better chemical structure compared to raw materials, making hydrothermal carbonization an increasingly important process.

Another proposed method for the thermal degradation of leather waste is combustion, a fully exothermic process studied on a micro-laboratory scale using thermogravimetric analysis (TGA) (Vershinina et al., 2022). On a larger scale, leather shavings were combusted in a 100 kW boiler at temperatures ranging from 20 to 1000°C, with heat produced by electric heaters preheating the combustion air (Fang et al., 2018). The process was initiated by heating the reactor using a gas burner located at the reactor's base. A series of experiments has been carried out in a 0.1 MWt bubbling fluidized bed pilot plant (Bahillo et al., 2004). It was shown that despite having high nitrogen content, a low conversion rate of fuel-N to NO_x and N_2O was attained. Also, chromium was concentrated in the ash, and it was consistently found as Cr^{III+} while no presence of Cr^{VI+} was detected.

Co-combustion was also explored while tannery waste was thermally degraded alongside hardwood pellets (Kluska et al., 2018). This method showed limited potential for industrial application due to the large amount of additive required to sustain combustion, which exceeded the weight of the waste being processed.

Tannery waste presents several challenges, including variability in particle size, low bulk density, irregular shapes, and high moisture content, which can increase energy consumption during processing. In this work, the authors propose a thermal degradation route for the industrial-scale recycling of tannery waste, providing a comprehensive analysis of the waste stream, energy output, and economic feasibility. Through collaboration with industry partners, practical methods for recovering energy from tannery waste were developed, and energy balance analyses identified the most cost-effective solutions.

This study offers an overview of thermal degradation methods, waste characteristics, and their properties, based on data from an industrial-scale tannery in Poland that processes cowhides using both the wet white and wet blue methods, from raw material to finished product (Wrzesińska-Jędrusiak et al., 2023). The characteristics of the waste suggest that various thermal degradation processes, such as pyrolysis, torrefaction, combustion, and gasification, could be viable options for waste management.

To the best of the authors' knowledge, this is the first comprehensive analysis of the technological process cycles and waste streams generated in a tannery, including detailed and exhaustive characterization. While the literature contains few examples of industrial-scale waste management (Thirugnana et al., 2023; Jiang et al., 2016), most studies focus on laboratory-scale solutions. The various processes and technological operations involved in leather tanning are often not precisely described or characterized in existing literature.

The scientific hypothesis is that implementation of a closed-loop system in the tanning industry can significantly reduce waste disposal costs and environmental impact while optimizing energy recovery through thermochemical processes. This work presents a comprehensive analysis of waste streams, energy balances, and economic feasibility based on data from an industrial tannery in Poland. Through collaboration with industry partners, the study identifies the most cost-effective solutions for energy recovery. The findings represent one of the first exhaustive analyses of tannery waste streams on an industrial scale, addressing gaps in literature, which predominantly focuses on laboratory-scale solutions.

2. Materials and methods

This study focuses on investigating the potential for energy recovery from tannery waste using thermochemical processes such as combustion, pyrolysis, and gasification, based on data from an actual tannery in Poland. This section characterizes selected waste fractions from the tannery industry and outlines the methodology of the conducted analyses.

2.1. Materials

Waste is generated at various stages throughout the tanning process, and its characteristics differ depending on the point of origin. These variations are reflected in both the chemical properties and the physical form of the waste. The chemical composition changes as different substances are gradually introduced during the production of finished leather products, including dyes, softening agents, waxes, impregnation materials, fats, tanning agents, basecoats, and topcoats. The physical form of the waste also varies widely, ranging from dust and shavings to scraps, thin sheets, and large pieces of leather measuring several thousand squares centimetres.

In this study, mainstream solid waste from the tannery industry in Poland was used as raw material. Table 1 presents the various types of solid waste, including shaving waste (WB/WW), crude trimming waste (mix), trimming waste (mix), split waste crust (mix), offcuts (mix), dust leather (mix), and tannery sludge. Each waste type is characterized by different shapes and sizes. For the physicochemical analysis, the samples were pre-processed through shredding to homogenize the size and shape of the particles.

2.1.1. Shaving waste

Shaving waste produced during leather processing is characterized by high humidity, around 50 %. Shavings are generated in separate streams depending on whether the leather is tanned as wet white or wet blue (Figure S1). This waste has an irregular shape, but generally, the thickness of a single piece does not exceed 1 mm, the width is less than 1 cm, and the length is several centimetres. Shavings are considered a homogeneous fuel with minimal impurities, mainly in the form of leather scraps. Due to their mechanical properties, shavings can be granulated without the need for grinding or binders. Granulation can be performed without prior drying, as completely removing moisture decreases the efficiency of the granulation process.

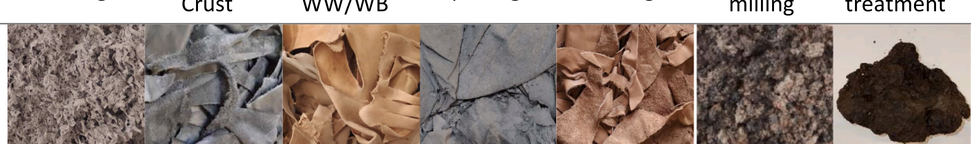
2.1.2. Trimming waste

Trimming waste consists of four streams: hides from both the wet white (WW) and wet blue (WB) processes, along with two additional types of waste labelled as "crust" (Figures S2-S3). These crust waste streams are generated after the dyeing and re-tanning processes and have significantly lower humidity, with a water content of around 10 %, compared to non-crust waste, which has a 50 % water content. The primary difference between wet white and wet blue hides, before re-tanning or tanning, is that they become much less elastic after drying.

2.1.3. Split waste leather

Split waste leather is characterized by low moisture content (12 %). Unlike shavings, split waste exits the technological process as a pre-mixed stream from both wet blue and wet white tanning processes. The splits are thin films, less than 1 mm thick, with areas ranging from several to several hundred squares centimetres. This waste is challenging to homogenize and can hinder transport within disposal

Table 1
Stream of the solid waste from the tannery industry.

	SHAVING WASTE WB/WW	TRIMMING WASTE crust (mix) WB/ WW	TRIMMING WASTE (mix) WB/WW	SPLIT WASTE crust (mix)	OFFCUTS (mix) WB/WW	DUST LEATHER (mix) WB/WW	TANNERY SLUDGE
Max. size [mm]	1 x 10 x 200	3 x 50 x 100	3 x 50 x 100	1 x 300 x 300	nd	1 x 1 x1	
Granulation without shredding	Yes	No	No	Yes / No	No	Yes	Yes
Part of the process	Shaving	Trimming Crust	Trimming WW/WB	Splitting	Cutting	Dedusting/ milling	Wastewater treatment
Photo							

facilities. Due to the mechanical properties and small thickness of the splits, they can be crushed with relatively low energy consumption. A challenge in shredding the splits is the presence of contaminants, such as full-thickness leather particles. The waste splits and contaminants are shown below. The average density of wet splits is 143.5 kg/m^3 . In their original form, split waste poses difficulties in granulation, as the pellets tend to crumble, and the process is slower compared to shavings or dust. After adding moisture, the splits become easier to granulate. In this study, wet blue and wet white split waste were mixed (Figure S4).

2.1.4. The offcuts

Offcuts are waste generated during the final production stage. Chemically, they are identical to finished leather products and are produced when leather elements are cut into shapes for sewing the final products. This waste has low moisture content and highly irregular shapes (Figure S5). Aside from the finished leather product itself, offcuts are the most chemically rich waste, having undergone the full tanning process, including re-tanning, pasting, and topcoat application.

2.1.5. Leather dust

Leather dust is the smallest solid waste stream generated during leather manufacturing (Figure S6), originating from both wet blue and wet white processes. It constitutes a minimal portion of the total solid waste, accounting for about 1 % by weight, with a moisture content of around 10 %. The dust is finely divided, which simplifies granulation, though its geometry leads to a low bulk density, averaging 121.5 kg/m^3 for wet waste. Due to its low water content, the dust forms granules with poor mechanical properties, characterized by low hardness and a high content of fine particles. Adding water (20 % of the dust mass) significantly improves granulation quality, resulting in a higher proportion of durable granules, fewer fine particles, and better mechanical properties.

2.1.6. Tannery sludge

Tannery sludge is a by-product generated in the tannery's treatment plant. It has an extremely high moisture content of around 70 % and forms compacted structures as a result of the mechanical dewatering of the water suspension containing silt. Although the silt consists of extremely fine particles, after pressing, it emerges as a cohesive, compact mass (Figure S7).

2.2. Physicochemical analysis of tannery waste

The elemental composition of the tannery waste was determined using a CHNS-O analyser (Flash 2000, Thermo Scientific, USA). Moisture content was measured with a Mettler Toledo moisture analyser, while the calorific value was assessed using a KL-12 MN calorimeter (PRECYZJA-BIT, Poland). Proximate analysis of the raw materials—including bulk density, dry biomass density, and ash content—was conducted in accordance with Polish Standard PN-EN 15403:2011. The morphology of the materials was examined via scanning electron microscopy (SEM), using a Hitachi SU3500.

The objective of this research is to characterize the waste streams generated by the tannery industry and evaluate the feasibility of recycling them on an industrial scale. To achieve this, it is essential to analyze the composition of the solid residue fractions (Table 2).

The proximate and ultimate analyses of the samples revealed significant variations in the characteristics of the tannery waste streams. The volume of each waste stream should be considered when developing an optimal waste management solution. Among the various waste types, split waste crust, dust, and offcuts exhibited the lowest moisture content (12.4, 11.3, and 12.0 wt%), whereas sludge contained as much as 70.9 wt% moisture. This wide range in moisture levels suggests that a drying process, along with grinding, may be required in the initial phase of treatment. For thermal degradation processes, combining different solid tannery wastes may be necessary. For granulation, higher moisture content could actually enhance sample formation.

In the context of potential thermal degradation, the ash content of the samples—reflecting the mineral and inorganic fractions—is a critical factor. The fixed carbon values offer insight into the carbon content and the waste's potential as an energy source during thermal conversion. Sludge waste had the highest ash content (17.2 wt%), which would remain as residue post-thermal conversion, while other waste streams had lower ash contents: dust (5.6 wt%), split waste crust (4.2 wt%), and offcuts, trimming waste, and shaving waste (WW), which were all around 6.0 wt%.

The ultimate analysis further confirmed carbon content ranging from 38.2 to 58.2 wt%, demonstrating that tannery waste could serve as a valuable energy source in thermal conversion processes. The bound oxygen content (23.2–36.5 wt%) is also notable, as it can be released during combustion, aiding the oxidation and conversion processes. Sludge waste showed markedly different results compared to the other waste streams, with 26.2 wt% carbon, 53.2 wt% bound oxygen, and significantly high moisture and ash contents. As sludge originates from the wastewater treatment process, its composition is distinct from the other waste types. Future experimental work will explore the effects of incorporating sludge into other waste streams, given its relatively low potential for energy conversion.

Given the goal of this work—finding an efficient solution for the energy management of solid tannery waste on an industrial scale—bulk density is a key initial parameter (Table 3). Bulk density influences both the volume of waste generated and the storage requirements at the plant. From an economic standpoint, a higher bulk density is advantageous, but the total volume of waste streams must also be considered. In the case of sludge, which has a bulk density of 585.6 kg/m^3 , the high value is attributed to the large amount of retained water, rather than concentrated energy. On the other hand, waste streams such as dust (82.5 kg/m^3), offcuts (71.5 kg/m^3), and trimming crusts from WW

Table 2
Proximate and ultimate analysis of raw materials and solid tannery waste.

Tannery stream waste	Shaving waste WW	Shaving waste WB	Trimming waste (mix)	Trimming crust WB	Trimming crust WW	Split waste crust (mix)	Offcuts (mix)	Dust leather	Sludge
Proximate analysis (wt%)									
Fixed carbon	9.8	4.4	20.7	40.2	45.5	54.9	53.5	53.5	0.3
Volatile matte	35.8	44.2	38.1	29.1	29.1	28.5	29.0	29.6	11.5
Ash	6.2	9.1	6.0	10.4	8.9	4.2	6.2	5.6	17.2
Moisture	48.1	42.2	35.2	20.4	16.6	12.4	12.0	11.3	70.9
Ultimate analysis (wt%)									
Carbon	42.3	38.2	42.9	42.9	45.0	52.9	50.0	58.3	26.2
Hydrogen	5.7	5.1	6.0	5.3	6.2	6.6	6.3	7.1	2.4
Nitrogen	10.0	11.1	11.4	12.9	11.4	6.7	10.2	8.0	1.0
Oxygen*	35.8	36.4	33.7	28.5	28.5	29.6	27.3	21.0	53.2

* O (wt%) = 100 – (C+H+N + Ash)

Table 3
Higher heating value for waste leather streams.

	Shaving waste WW	Shaving waste WB	Trimming waste (mix)	Trimming crust WB	Trimming crust WW	Split waste crust (mix)	Offcuts (mix)	Dust leather	Sludge
Bulk density, (kg/ m^3)	171.3	219.4	114.0	62.3	65.7	107.4	71.5	82.5	585.6
HHV[1,] (MJ/kg)	14.8	12.7	16.7	15.9	13.6	30.5	20.5	25.2	8.9

[1] Higher heating value.

(65.7 kg/m^3) and WB (62.3 kg/m^3) exhibit low bulk densities due to their distinct physicochemical properties.

The most critical parameter for energy recovery from solid tannery waste is the calorific value (HHV). The samples analyzed in this study showed good heat of combustion values, comparable to typical biomass fuels. Sludge had the lowest calorific value (8.9 MJ/kg), while split waste crust demonstrated the highest (30.5 MJ/kg). The low calorific value of sludge is due to its origin as a residue from the wastewater treatment process, containing significant amounts of inorganic matter. On average, waste generated throughout the tannery process exhibits a calorific value of approximately 15 MJ/kg, with streams closer to the final product achieving higher values, around 25 MJ/kg.

The primary focus of this work is the energy management of tannery waste. During leather tanning, chromium is introduced into the leather, which must be considered in subsequent heat treatment processes. Planned research involving pyrolysis and combustion will evaluate whether these energy-based methods for neutralizing and reducing waste volume are feasible on an industrial scale. Ideally, chromium will remain in the ash and can be safely deposited in a landfill.

To assess heavy metal content, particularly chromium, X-ray fluorescence (XRF) tests were conducted, and the results are summarized in Table 4. These tests confirm the presence of chromium due to the use of chromium-containing dyes during the wet blue stage. Chromium concentrations were detected in shaving waste WB (5.2 wt%), trimming crust WB (4.1 wt%), and various mixed waste samples, including trimming waste (mix) (2.9 wt%), dust (1.1 wt%), and offcuts (mix) (3.2 wt %). Elevated sulfur content was noted in most analyzed tannery wastes (0.8–3.2 wt%). High sulfur levels can pose problems in high-temperature processes due to increased SO_2 emissions, while in low-temperature processes, sulfur generally remains in the ash (Knudsen et al., 2004). Excessive sulfur, combined with alkaline elements (e.g., Ca, K, Na), may also contribute to equipment corrosion due to the formation of low-melting salts (Kazimierski et al. 2022).

The diversity in physicochemical properties and the variety of waste fractions suggest that an effective approach may involve using mixtures of solid waste or targeting the most substantial waste streams or those presenting the greatest management challenges. Leather waste alone does not support autothermal combustion, despite its adequate higher heating value. To address this issue, the authors propose enhancing the fuel's flammability by incorporating additives into the leather waste to create premixed pellets. Previous research results (Turzyński et al., 2023) demonstrated that even a minor addition biomass stabilized the combustion process without causing sinter formation. Ash analysis revealed that for chromium-containing waste, a significant portion of chromium remained in the ash as non-toxic Cr_2O_3.

2.3. Industrial technology scheme and energy balance

During the leather tanning process, vegetable tannins (for wet-white) or chromium III (for wet-blue) are used as tanning agents (Kanth et al., 2009). The tanning process is preceded by several chemical and mechanical operations designed to refine, preserve, and enhance the leather's properties, including its touch and appearance. Initial preparation and chemical preservation of hides occur at the slaughterhouse, after which the hides are sent to the tannery (Wu et al., 2017).

Following calcification of the hides, the fleshing operation is performed under strongly alkaline conditions (pH 12–13) to remove muscle and fat tissue adhering to the leather (Flemming, 2013). After calcification and de-fleshing, hides are split using splitters, pickled, and tanned in chromium solutions. The pickling process further lowers the pH of the hides. Post-tanning, the by-products consist of impregnated leather fragments, which are non-biodegradable and may contain chromium (III) (Beltrán-Prieto et al., 2012).

This section examines a mass and energy balance of the entire industrial tanning process, summarizing the characteristics of various waste streams. The sequence of operations can vary depending on the tannery and hide type. An exemplary technological scheme based on data from the Polish tannery industry is illustrated below (Fig. 1). Input data (shown on the right-hand side) includes the quantities of processed material, energy, and water for each production process. To facilitate the observation of losses and products obtained, we assumed an input of 1000 kg of raw hides.

The production process is diverse, and the amounts of generated waste depend on the specific process batch; the presented data represents the average of annual industrial data. For every 1000 kg of hides processed, approximately 175 kg of final product is obtained. This results in about 825 kg of various waste streams, constituting nearly 83 % of the initial batch weight. Significant amounts of sludge are produced during treatment, which is a particularly problematic waste group. This study also analyzes an example of tannery sludge, generated with the wastewater treatment process.

The tannery's technological process involves several key operations.

Table 4
XRF analysis of raw materials and solid tannery waste.

[wt %]	Shaving waste WW	Shaving waste WB	Trimming waste (mix)	Trimming crust WB	Trimming crust WW	Split waste crust (mix)	Offcuts (mix)	Dust leather	Sludge
Fe	nd	0.07	0.10	0.04	nd	0.05	0.20	0.14	14.9
Ca	0.90	0.90	0.30	0.30	0.20	0.20	0.10	0.30	1.40
Si	2.70	nd	nd	nd	4.50	0.54	nd	0.20	nd
S	2.50	3.20	0.80	1.80	1.60	3.03	1.40	1.30	nd
Cr	nd	5.20	2.90	4.10	nd	nd	3.20	1.10	nd
P	nd	nd	nd	0.10	nd	0.30	nd	0.11	0.40

*nd – not detected

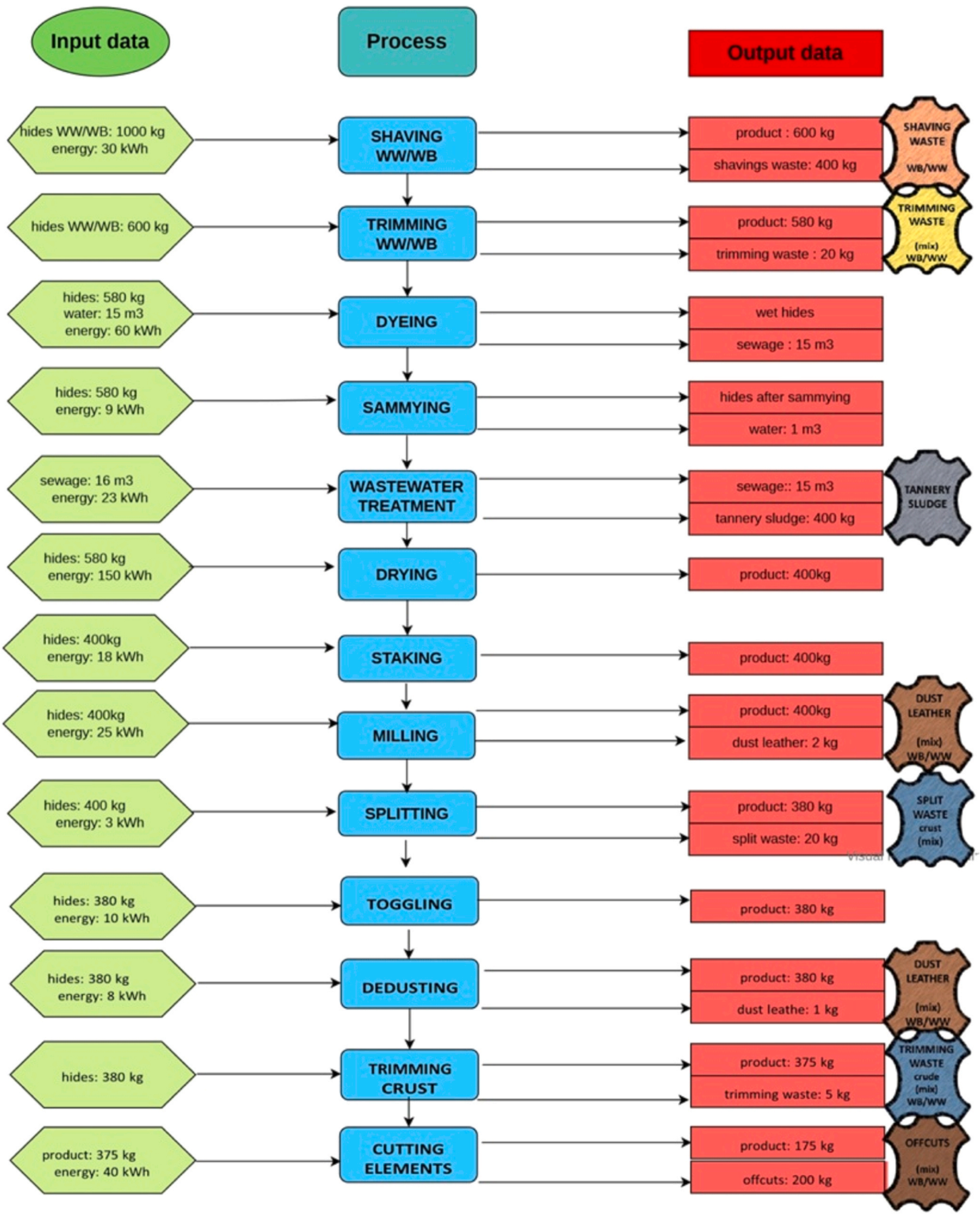


Fig. 1. Flow sheet of product, energy, and effluent inventory for leather production at a tannery.

It begins with the shaving process, which adjusts the thickness of the hides to meet specific requirements. This is followed by a trimming operation (WW/WB), which smooths the hide's profile by removing any unnecessary pieces left over from shaving. These remnants form a smaller portion of the overall post-production waste. Next, the hides undergo dyeing and re-tanning, a chemical process that alters the structure of the leather, giving it the desired tactile and quality characteristics. For every 580 kg of hides, approximately 15 m^3 of water and 60 kWh of energy are required.

After dyeing, the hides are subjected to sammying and drying operations to reduce their moisture content. When comparing energy consumption, sammying requires 9 kWh, while drying consumes 150 kWh, making the dryers the most energy-intensive machines in the process—using nearly 20 times more energy than sammying. Other operations, such as splitting (30 kWh) and softening the leather through staking and milling, are less energy demanding. Auxiliary processes like toggling and de-dusting require minimal energy input.

The trimming of crust hides is a final cosmetic step, refining the hide's profile without requiring additional energy. At the end of the prefabrication process, the largest waste streams are produced during the cutting phase, where finished elements are cut out. Shavings and offcuts account for the majority of the waste, with shavings constituting 40 % and offcuts up to 50 % of the hides' input weight before cutting.

2.4. Thermal pathways for tannery waste management

The primary thermal processes for managing leather waste include combustion, gasification, pyrolysis, and torrefaction. The amount of oxidizing agent (oxygen or air) plays a crucial role in determining the characteristics of the waste transformation process.

When the air supply exceeds the stoichiometric requirement, it enhances the exothermic degradation of polymers, leading to high-temperature reactions ranging between 800°C and 1200°C. This elevated temperature, combined with an excess of oxidants, helps inhibit the formation of harmful dioxins in the exhaust gases. The main by-products of the process include heat and exhaust gases, such as CO_2, H_2O, CO, SO_2, NO and NO_2.

The main chemical reactions during the thermal degradation processes are presented below:

Pyrolysis process (Han et al., 2017):

$$\text{biomass} \rightarrow \text{char} + \text{oil} + \text{volatiles}\ (CO, H_2, H_2O, CO_2, CH_4, H_2S) \quad (1)$$

$$CH_{1.4}O_{0.6} \rightarrow C + CO + H_2O + H_2 + \text{other compounds} \quad (2)$$

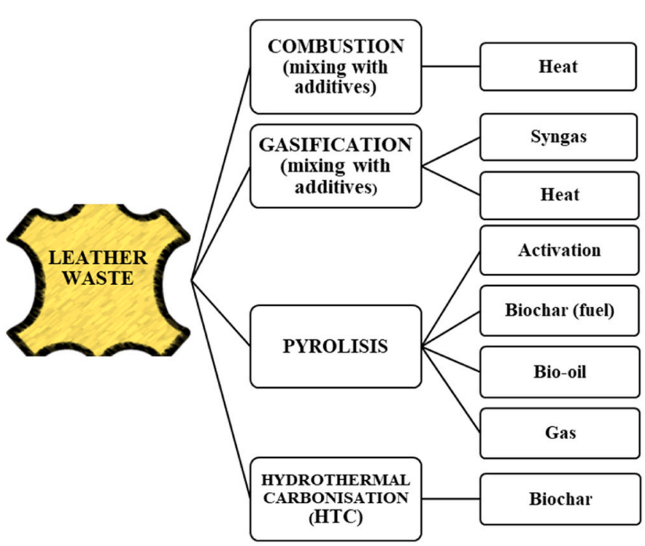


Fig. 2. Thermal recycling and routes of energy recovery from tannery waste.

Decomposition process:

$$\text{Char} \rightarrow C + H_2 + O_2 + N_2 + S + \text{ash} \quad (3)$$

Gasification process (Pilar González-Vázquez et al., 2021, Khonde et al., 2021):

$$\text{Carbon combustion reaction: } C_{(s)} + O_2 \rightarrow CO_2 \quad (4)$$

$$\text{Carbon partial oxidation reaction: } C_{(s)} + 0.5\ O_2 \rightarrow CO \quad (5)$$

$$\text{Water-gas reaction: } C_{(s)} + H_2O \rightarrow CO + H_2 \quad (6)$$

$$\text{Boudouard reaction: } C_{(s)} + CO_2 \rightarrow 2\ CO \quad (7)$$

$$\text{Methanation reaction: } C_{(s)} + 2H_2 \rightarrow CH_4 \quad (8)$$

$$\text{Water-gas shift reaction: } CO + H_2O \rightarrow CO_2 + H_2 \quad (9)$$

$$\text{Steam reforming reaction: } CH_4 + H_2O \rightarrow CO + 3H_2 \quad (10)$$

$$\text{Hydrogen oxidation: } H_2 + 0.5\ O_2 \rightarrow H_2O \quad (11)$$

$$\text{Carbon monoxide oxidation: } CO + 0.5\ O_2 \rightarrow CO_2 \quad (12)$$

$$\text{Methane oxidation: } CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O \quad (13)$$

Combustion process (Lewandowski et al., 2020):

$$\text{Biomass} + O_2\ (\text{stoichiometric amount}) \rightarrow \text{thermal energy} + \text{flue gas} \quad (14)$$

$$CH_{1.4}O_{0.6} + 1.05\ O_2 + (3.95\ N_2) \rightarrow CO_2 + 0.7\ H_2O + (3.95\ N_2) \quad (15)$$

Pyrolysis is a thermal degradation process that occurs in the absence of an oxidizing agent (such as air, steam, or oxygen) and at elevated temperatures (typically between 350°C and 800°C). While pyrolysis is an endothermic reaction, requiring heat input, it produces valuable by-products such as a liquid fraction and syngas, which can serve as energy sources for subsequent combustion processes. Gasification, which bridges the processes of combustion and pyrolysis, involves thermal conversion with an air-to-fuel ratio between 0 and 1, where steam acts as the oxidizing agent. In practice, gasification is carried out with an air ratio of 0.1–0.3 (Wang et al., 2015). Inside the gasifier, there is an anaerobic zone where pyrolysis occurs without oxygen. The main products of gasification are heat and syngas, composed primarily of carbon monoxide (CO) and hydrogen (H_2).

Another method, hydrothermal treatment, offers a way to produce fuel with improved calorific value while also reducing the volume of raw materials. It compacts waste, enhancing its energy density (Peng et al., 2016).

Combustion, the oldest and most established thermal process, is widely applied at an industrial scale, with technological advancements making it suitable for various waste streams. There has been a growing demand for incinerators and combustion boilers that handle not only high-energy waste fractions, such as refuse-derived fuel (RDF), but also other industrial waste (Kanth et al., 2009). Combustion is an exothermic process, extracting energy from waste streams, which can be repurposed for initial stages like drying. It also offers the advantage of reducing waste volume and eliminating biologically active residues.

Leather waste presents certain challenges for combustion. Its high moisture content, irregular fragmentation, and inability to sustain combustion independently complicate the process. In the absence of proper intervention, leather waste tends to smolder, burn inefficiently with a low flame, and produce a large amount of pollutants. By applying processes such as fragmentation, drying, granulation and enrichment, the physicochemical properties of the waste can be improved, facilitating more efficient combustion.

Despite the relatively good calorific value of leather waste, it struggles to support combustion on its own. Solutions to these challenges include three main approaches: combustion aided by external heat sources, co-combustion with other fuels, and the production of fuel from homogeneous mixtures of ground leather waste combined with combustion-supporting additives (Turzyński et al., 2023). The first method involves the use of clean leather waste (without admixtures), where additional heat initiates pyrolysis, creating external heat and facilitating the burning of the residual char.

Next chapter outlines the properties of the waste streams and provides foundational data for future investigations into combustion and pyrolysis of leather waste, offering potential solutions for thermal waste management on an industrial scale.

3. Results and discussion of energy balance of tannery waste

The implementation of a closed-loop system in the tanning industry presents a viable strategy for enhancing both sustainability and economic efficiency. This study, based on real data from a Polish tannery, demonstrates that utilizing thermal processes such as combustion, pyrolysis, and gasification can significantly reduce waste storage needs while recovering valuable energy (Alcazar-Ruiz et al., 2022; Vamvuka et al., 2023; Kazimierski et al., 2022). The efficiency of thermochemical waste conversion processes can vary depending on the type of process used. In this analysis, efficiency refers to the percentage of chemical energy in the fuel that is recovered through thermochemical conversion, measured with the final flue gas temperature at 200°C. For simplification, it is assumed that the device walls are adiabatic, as this avoids the complexity introduced by varying heat losses across devices of different scales. The highest efficiency is observed in direct combustion, where energy loss primarily occurs through chimney loss. The chimney loss is calculated using the following formula:

$$qA[\%] = (T_{gas}\ [^{\circ}C] - T_{amb}[^{\circ}C]) \times \left(\frac{A_1}{CO_2[\%]} + B\right) \tag{16}$$

where: qA is the chimney loss, T_{gas} – the flue gas temperature, T_{amb} – the temperature of the air used for combustion, A_1 and B - the Siegert coefficients.

Chimney loss (qA) refers to the portion of heat generated during combustion that is not recovered and is instead lost with the flue gas. This loss depends on the flue gas temperature, the air temperature used for combustion, and the CO_2 content in the exhaust. In this context, stoichiometric combustion is assumed, meaning the maximum possible CO_2 content for a given fuel was achieved. Calculations for energy recovery in industrial installations using the three main methods of thermal conversion were carried out using formula (16), with results presented in Fig. 3.

In direct combustion, efficiency is the difference between the energy in the fuel and the energy lost in the exhaust gas. The calculated combustion efficiency is 94 %. For simplification, due to similar volatile matter content and chemical composition, the Siegert coefficients used for tannery waste are the same as those used for wood. Due to heat losses from incomplete oxidation of the fuel's elemental components, gasification has lower energy efficiency than combustion.

In gasification, a sub-stoichiometric air ratio leads to the formation of carbon monoxide, reducing efficiency. Although the char could theoretically undergo further oxidation, incomplete oxidation lowers the process's efficiency. In this co-current gasification mode, the char residue accounts for 15 % of the charge weight, and all generator gas is combusted for energy recovery (Dudyński et al., 2021). The gasification process efficiency is calculated by subtracting the energy of

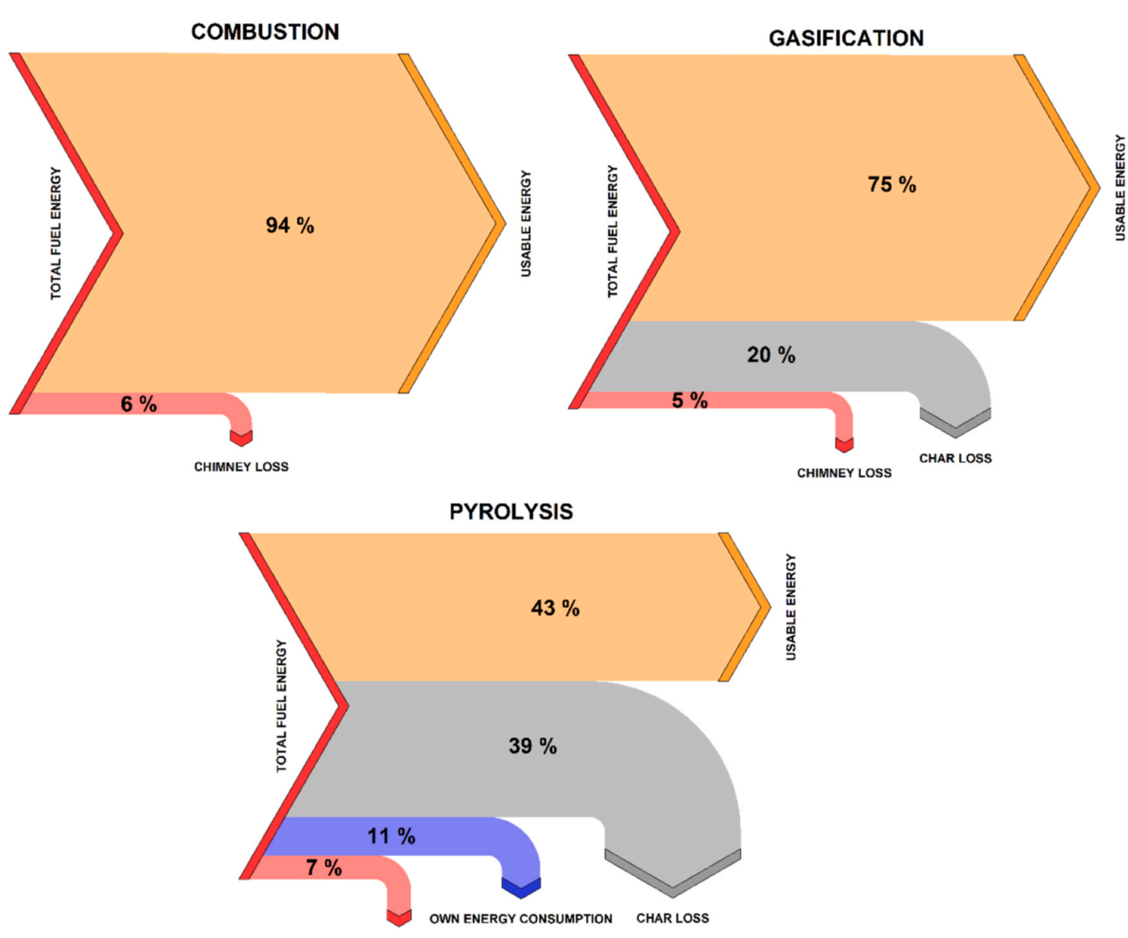


Fig. 3. The energy balance of main energy recycling routs for tannery waste.

non-oxidized fuel and the stack loss after burning generator gas from the fuel's total energy. The energy efficiency of the gasification process was estimated to be 75.0 %. The Siegert coefficients for generator gas combustion were assumed to be the same as those used for gas mixtures in coal coking.

Pyrolysis had the lowest energy efficiency, at 43 %. The char residue from pyrolysis is assumed to be 29.0 % of the charge mass, with a higher heating value (HHV) of 19.9 MJ/kg. The energy loss from under-burning the char is estimated at 38.7 %. Other factors reducing efficiency include the energy extracted from the system due to the caloric content of the char, pyrolysis gas combustion stack loss, and pyrolysis tar combustion stack loss. The amount of tars produced during tannery waste pyrolysis is approximately 10 % (Kluska et al., 2019). The energy consumption for the endothermic pyrolysis process and the losses during reactor heating further reduce efficiency. The heat required for pyrolysis is 0.37 MJ/kg, and the reactor heating efficiency is estimated at 20.0 %, meaning that 11.1 % of the fuel energy is consumed by the pyrolysis process (Roberts, 1971).

In this study combustion was chosen for its superior energy yield, being an exothermic process. Authors have previously shown (Turzyński et al., 2023) that combustion process of pelletized tannery waste improved with additives is not only possible but also provides a whole range of benefits. Experimental tests have shown that autothermal and complete combustion of tannery waste pellets can generate up to 3.5–6 GJ/m^3 of fuel while the precise dosage of additives can influence the ash sintering properties, effectively trapping chromium oxides in the ash (Cr_2O_3 content in shavings was 5.5 wt%, while in the ash after combustion 76.6 wt%). Additionally, gas analysis showed, that the NO_x concentration remains constant (~300 mg/Nm^3) while the SO_2 concentration decreases to as low as 95 mg/Nm^3 with the amount of added sawdust. In the present case, the energy generated from the combustion of all tannery waste streams was calculated; then to be used to produce both heat and electricity. Based on prior research on high-temperature Organic Rankine Cycle (ORC) systems, it was estimated that 3.3 % of the chemical energy contained in the waste can be converted into electricity, with the remaining heat used to dry the waste. The relatively low heat-to-electricity conversion efficiency is due to the small scale of the installation. Tannery waste alone is insufficient to power a steam turbine efficiently.

Thermal energy is utilized in the ORC system with an assumed cycle efficiency of 20 %. The practical conversion of heat into electricity is lower, owing to factors such as heat dissipation in the condenser, incomplete heat recovery from flue gases, and stack losses. The installation's scale significantly impacts the lower heat-to-electricity conversion compared to values seen in commercial power generation. A typical tannery does not generate enough waste or thermal power to justify using a conventional steam system. Thermal energy recovery was assumed to be handled by an ORC system, which has a lower installation cost. The efficiency of such a cycle should be considered—direct expansion cycles typically have an efficiency of 17 % (Klimaszewski et al., 2023), with the internal turbine efficiency reaching 81.3 % (Witanowski et al., 2023). In condensing and cogeneration modes, efficiencies may reach 76.5 %.

Drying processes should be divided into two independent categories: drying hides after dyeing (this energy demand is part of the process heat) and drying the waste separately. This division is necessary since a certain amount of heat is required for the process regardless of the waste being managed. The chosen waste management method—combustion—necessitates extra drying of the waste. Although the combustion process itself does not directly require additional electricity, a slight simplification was made. Depending on the technology used, electricity may be required to power fans, pumps, conveyors, and other components of the system. The energy consumption of these devices is relatively minor.

The Sankey diagram (Fig. 4) presents the electricity consumption for processing 1000 kg of leather, from pre-tanned hides to finished car upholstery elements. The initial shaving process consumes less than 30 kWh, accounting for less than 10 % of the total electricity consumption, while also producing the largest mass of waste. The most energy-intensive process is drying, consuming nearly 150 kWh per 1000 kg of hides. Other notable energy consumers include dyeing (around 60 kWh) and the final cutting process for upholstery elements (40 kWh). Additional processes, such as plating, softening, bracking, splitting, tightening, MACH, and de-dusting, collectively use about 25 % of the total electricity consumed in the entire production process.

Electricity demand can be partially covered by the energy produced in the ORC system (Fig. 5). With a total demand of around 350 kWh, the energy generated in a steam turbine system powered by waste can cover

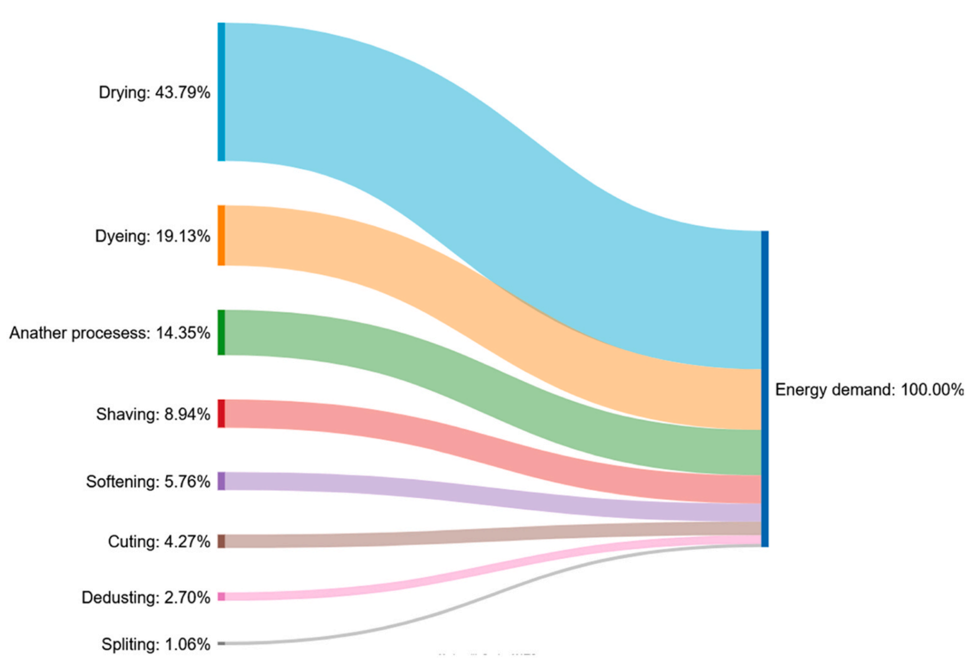


Fig. 4. The Sankey diagram illustrates the energy consumption throughout the tannery process, with the total energy consumption allocated across the various waste streams, representing 100 % of the overall input.

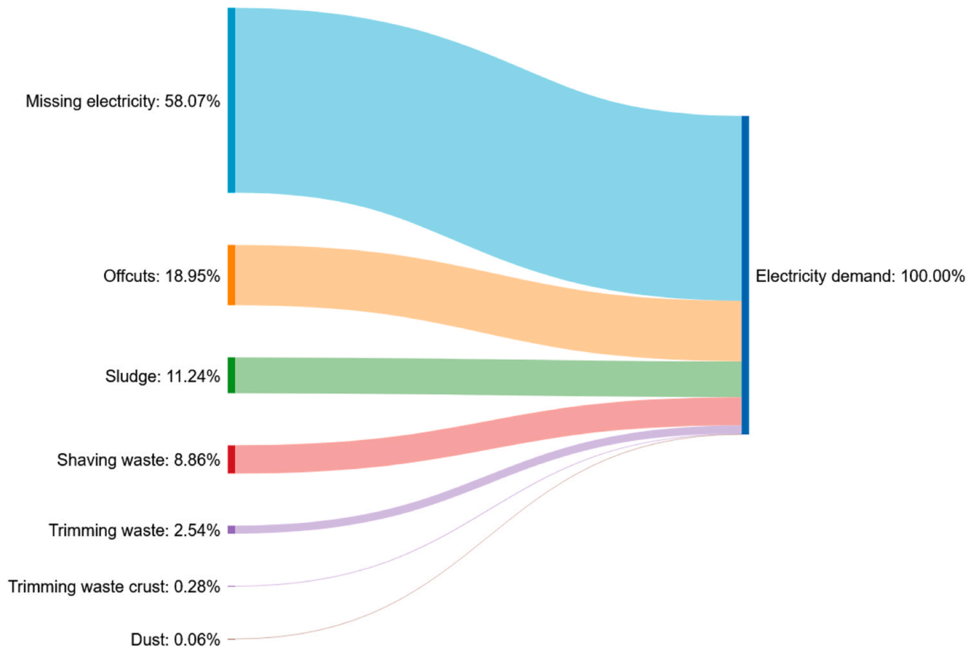


Fig. 5. The energy demand breakdown of technological processes in the tannery industry is illustrated based on the demand of total waste streams generated (100 %).

more than 40 % of the electricity demand. Of the 151.9 kWh that can theoretically be produced from waste from processing 1 ton of leather, the largest share is energy produced from offcuts (66.9 kWh), sludge (39.7 kWh) and shaving waste (31.3 kWh). Calculated with the assumption that all waste is used for heat production. The entire flue gas stream goes to the ORC system, in which, with an efficiency of 3.3 %, electricity is produced that satisfies 40 % of the demand for unit processes. This is beneficial in terms of the rational use of energy, waste management and economics.

The heat balance of technological processes in the tannery industry is shown in Fig. 6. The chemical energy derived from waste can supply approximately 40 % of the electricity needed for the process, resulting in a positive heat balance. The heat generated from waste exceeds the total heat demand in the production of finished leather and fully meets the requirements of the drying plant used to prepare waste for incineration. The largest amount of thermal energy is obtained from the combustion of offcuts, which can be easily utilized as fuel due to their low moisture content (around 12 %). In contrast, tannery sludge from wastewater treatment has the highest moisture content among all waste streams, at approximately 70 %.

The heat required for drying can be sourced from the waste combustion process, eliminating the need to purchase fuel or electricity to heat the drying medium. The thermal energy generated from incinerating tannery sludge exceeds the amount needed for its drying process. By transitioning from landfill disposal to energy recovery, tanneries can not only lower operational costs but also contribute to a more sustainable industry. The proposed calculations demonstrate how engineering solutions can optimize resource efficiency, minimize environmental impact, and pave the way for broader adoption of circular economy principles in the leather industry and beyond.

4. Conclusion

In conclusion, this study underscores the significant scientific and practical contributions of utilizing tannery waste for energy recovery. Based on real data from a Polish tannery, the findings confirm that the tanning industry generates substantial waste—approximately 825 kg per 175 kg of finished leather—which can be thermally treated to

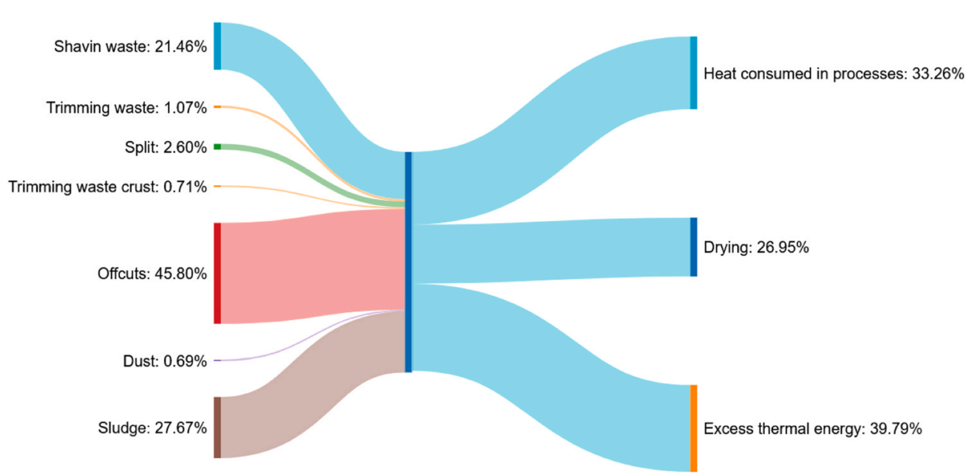


Fig. 6. The heat balance diagram for technological processes in the tannery industry.

maximize energy recovery. The findings highlight that tannery waste, which includes substantial amounts of offcuts and sludge, can be effectively converted into energy through combustion, gasification, and pyrolysis, with combustion demonstrating the highest energy yield of 94 %. This not only addresses the industry's waste management challenges but also offers economic benefits by meeting heating demands and partially offsetting electricity needs through an ORC system. The significant energy demands of processes such as TAIC, dyeing, and cutting, as well as the specific requirements for offcuts (66.9 kWel) and shaving waste (31.3 kWel), further emphasize the necessity of efficient waste management. Moreover, the study quantitatively demonstrates how integrating waste heat into an ORC system can reduce the tannery's electricity consumption by 40 %, illustrating both economic viability and environmental sustainability. By converting waste into valuable energy resources, this approach not only reduces operational costs but also lowers the carbon footprint associated with traditional waste disposal methods.

Moving forward, future research should focus on optimizing waste processing techniques, such as developing high-energy pellets and refining advanced thermal treatment methods. These efforts will contribute to sustainable end-of-life strategies for tannery waste, aligning with circular economy principles and enhancing overall resource efficiency within the industry. This research lays the groundwork for future advancements in tannery waste utilization.

CRediT authorship contribution statement

Kardaś Dariusz: Writing – original draft, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Paulina Bandrów:** Writing- orginal draft, Data curation, Visualisation. **Turzyński Tomasz:** Writing – review & editing, Methotology, Writing – original draft, Formal analysis, Conceptualization. **Barczak Beata:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Januszewicz Katarzyna:** Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Kazimierski Paweł:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fbp.2025.03.009.

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