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Leather waste valorization as solid fuel for thermal energy

Valorização de resíduos de couro como combustível sólido para energia térmica

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ABSTRACT: Solid waste is an attractive renewable resource for thermal energy systems in the effort to reduce greenhouse gases (GHG) emissions globally. Footwear industries play a significant role in many countries, and generate a huge amount of Leather Solid Waste (LSW) in forms of scraps and losses as strips, sides, or edges, powdered or compacted. The objective of this work was to investigate the characteristics of LSW, originated in footwear industries, as it serves as a solid fuel that can be converted into thermal energy. Experimental tests for evaluation of solid fuel characteristics included proximate and ultimate analysis, high heating value, bulk and energy density, and also the particle size distribution. The bulk and energy density achieved were low (110 kg.m^{-3} and 2 GJ.m^{-3}, respectively), and densification could provide a more interesting solid fuel. The LSW has characteristics similar to biomass, particulary in terms of volatile matter (76%) and fixed carbon (17%) on a dry basis, and for hydrogen/carbon (H/C) and oxygen/carbon (O/C) ratios in the same magnitude as *Eucalyptus* wood. The high ash content (7%) demands the same operational care in thermal equipment, as in sugarcane bagasse combustion. The achieved moisture of 12% showed that it does not require artificial drying for combustion. LSW has a good high heating value (HHV), of approximately 20 MJ.kg^{-1}, which is higher compared to typical biomasses such as sugarcane bagasse or agricultural residues. All the relevant characteristics for the good quality of a solid fuel are present in the evaluated LSW.

Keywords: Combustion; Environmental pollution; Incineration; Recycling; Waste-to-energy.

RESUMO: Os resíduos sólidos são um recurso renovável atraente para sistemas de energia térmica no esforço para reduzir as emissões de gases de efeito estufa (GEE) globalmente. As indústrias de calçados desempenham um papel significativo em muitos países e geram uma enorme quantidade de resíduos sólidos de couro (RSC) na forma de sobras e perdas como tiras, laterais ou bordas, em pó ou compactadas. O objetivo do trabalho foi investigar as características dos RSC, originado nas indústrias de calçados, pois serve como um combustível sólido que pode ser convertido em energia térmica. Os ensaios experimentais para avaliação das características do combustível sólido incluíram análise imediata e elementar, poder calorífico, densidade aparente e energética, e também a distribuição do tamanho de partículas. As densidades aparente e energética alcançadas foram baixas (110 kg.m^{-3} e 2 GJ.m^{-3}, respectivamente), sendo que a densificação poderia fornecer um combustível sólido mais interessante. O RSC analisado apresentou características semelhantes a outras biomassas, principalmente em termos de material volátil (76%) e carbono fixo (17%) em base seca, e para relações hidrogênio/carbono (H/C) e oxigênio/carbono (O/C) na mesma magnitude para madeira de eucalipto. O alto teor de cinzas (7%) exige os mesmos cuidados operacionais em equipamentos térmicos, como na combustão do bagaço da cana-de-açúcar. A umidade alcançada de 12%, mostrou que não requer secagem artificial para combustão. O RSC possui um bom valor de poder calorífico superior (PCS), de aproximadamente 20 MJ.kg^{-1}, é maior em comparação a biomassas típicas como bagaço de cana-de-açúcar ou resíduos agrícolas. Todas as características relevantes para a boa qualidade de um combustível sólido estão presentes no RSC avaliado.

Palavras-chave: Combustão; Incineração; Poluição ambiental; Reciclagem; Resíduos para energia.

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1 INTRODUCTION

Waste valorization is an attractive way to integrate energy into renewable resources and reduce greenhouse gasses (GHG) emissions globally. That is in line with the international energy program and policies to an energy transition that looks for local and renewable sources, while two-thirds of the world population will be living in urban areas by 2050 (Angeli *et al*., 2018). Organic wastes are about 50% of the urban scale, thus providing high carbon content as the ones available in biomass; after collecting, storage, and pretreatment processes - as grinding or shredding, and eventual drying, may result in final products as solid biofuels or fertilizers. Leather is a typical Municipal Solid Waste (MSW) that has biomass-like energy and physical characteristics. Also, large quantities of it are available from leather-making industries as shoe residues (footwear industry).

The leather production chain in Brazil is quite significant, with at least 450 tanneries, 1100 producers of footwear components, 2300 companies that are manufacturers of leather artifacts, and 6000 shoe companies (Corrêa, 2001). The country's cattle heard is the biggest in the world, around 218 million heads (IBGE, 2020), mostly used for meat, milk, leather, and other derivatives. Brazil comes in 1st place in terms of footwear production outside of Asia (China, India, Vietnam, and Indonesia), and is ranked 5th globally in 2022 (ABICALÇADOS, 2024). In its own territory, considering the revenue generated in the Brazilian footwear industry, the ranking sequence is Ceará (CE), Rio Grande do Sul (RS), and Paraíba (PB) states, 26.0%, 23.9% and, 15.1%, respectively

The main regions of the Brazilian footwear industry, that use bovine leather as the raw material of their products, are the city of Franca-SP and Rio dos Sinos-RS valley (Alves; Barbosa, 2013; Pedde *et al*., 2014). Consequently, a significant amount of industrial waste, such as shavings and scrapings, the last one is a by-product resulting from leather parts that correspond to the flesh side and are tanned and processed, according to definition in NBR 14548 (ABNT, 2020). Thus, small leather fragments from processing are wastes in the manufacturing. The footwear industry in southern Brazil (Rio Grande do Sul, Santa Catarina, and Paraná states) alone discards more than 200 tons per month (Zattera *et al*., 2005).

The term solid waste refers to any material, substance, or discarded objects that are the result of human activities in society. That follows the definition of the National Solid Waste Policy – NSWP, Brazilian Federal Law 12.305/2010 and Federal Decree 10.936/2022 (Brasil, 2010, 2022). As for its origin, leather waste is classified as industrial waste, that is, generated in production processes and industrial installations. In Brazil, according to the Brazilian Association of Technical Standards, the NBR 10.004 standard (ABNT, 2004), specific to the leather-footwear industry as a source of three hazardous wastes: (a) Leather shavings from chrome-tanned leather (code K193); (b) Sawdust and leather powders from chrome-tanned leather (code K194), and; (c) Sludge from the treatment of liquid effluents originating in the chrome-tanned leather process (code K195). Therefore, disposal in industrial landfills is recommended due to their high polluting potential.

Industrial tannery residue uses in crops as a viable alternative for the disposal of lower environmental pollution was investigated for recycling composted tannery sludge and mixtures as soil fertilizer to improve productivity (Souza *et al*., 2017). There are low-cost options for chromium removal from leather residues, as adsorption using agriculture wastes in tannery wastewater, then avoiding environmental pollution and allowing chromium recovery (Nue-E-Alm *et al*., 2020). Leather fragments and from wet-blue powder are feasible options to combine with recycling the waste of polypropylene or thermoplastic starch to obtain alternative materials with improved mechanical properties (Rizzato *et al*., 2020; Pompei *et al*., 2020). In food industries, leather is used in the production of gelatin, whose reuse of water and caustic soda could be investigated.

Reuse and recycling are priorities for waste management (Brasil, 2010), therefore it is important to identify and seek alternatives for the technical and economic feasibility of scrap and losses from the production process, transforming into new products. The treatment is the next option as final destination environmentally friendly, and it includes composting, recovery, and energy use, among other options admitted by the competent agencies. There are several processes available, typically chemical or thermo-chemical, both for chromium removal before the effective disposal of these residues by the tannery and stainless-steel industries or its recovery (Ma *et al*., 2018; Dávila-Martinez *et al*., 2017), aiming to comply with the legislation in force for trivalent and hexavalent chromium ions (Cr^{+3} and Cr^{+6}). In general, reuse of leather waste after footwear manufacturing occurs for soil disposal or thermal energy via combustion (Tatano *et al*., 2012).

From the mass and energy viewpoints, the amount of scrap and losses in the footwear industry is also an opportunity for the appropriate, beneficial, and valued destination of these materials. The use of these residues in combustion processes for energy purposes has been documented in literature since at least 1930 (U.S. Bureau of Standard Notes, 1930). Current investigations include: Incineration for disposal in environmental compliance (Kavouras *et al*., 2015), thermogravimetric analysis for leather on the composition of MSW (Tang *et al*., 2015), combined combustion of leather and wood pellets (Kluska; Turzynski; Kardas, 2018; Kluska *et al*., 2020), emissions from the combustion blends of leather, coal and sewage sludge (Zhan *et al*., 2019) or raw material in the production of biodiesel and biogas (Lazaroiu *et al*., 2017). An innovative approach is biochar de-chroming, which eliminates oxygen in the leather to create biochar, while high-temperature pyrolysis produces a high quantity of organic products (Jiang; Liu; Han, 2016).

All these studies focus on waste from leather processing industries, but none of them refer to waste from the footwear industry. Currently, a better destination of residues contributes to Sustainable Developments Goals (SDG) from the United Nations 2030 Agenda, as*"Affordable and clean energy - SDG 7, "Industry, innovation and infrastructure - SDG 9*, and *"Responsible consumption and production - SDG 12* (NU Brasil, 2025).

In this context, the objective of this work was to investigate the characteristics of LSW, originated in footwear industries, as it serves as a solid fuel that can be converted into thermal energy.

2 MATERIAL AND METHODS

2.1 SAMPLES: ORIGIN, PARTICLE SIZE AND DENSITY

The leather solid waste (LSW) originates in footwear industries at Sinos river valley (São Leopoldo, Rio Grande do Sul, Brazil). The procedures for sample preparation are according to the following technical standards for proximate and ultimate analysis, and experimental determination of the high heating value (HHV) described in the NBR 6922 and NBR 7402 standards (ABNT, 1981, 1982), those are the closest approach to biomass and solid fuels available in Brazil at the time of this investigation.

Original samples received from footwear industry are around 2 kg, and passed through a knife mill for size uniformity (Figure 1).

Figure 1. LSW samples after grinding and sieves

The particle size determination (or granulometry) was based on CEMP 081 (ABIFA, 2015) and NBR 3310-1 (ABNT, 2010) standards; the procedure used a set of twelve standard ASTM/Mesh Tyler "A" series sieves (circular shape, stainless steel and 2" or 50.8 mm height) and bottom base without perforation (blind bottom) were used. The material weighing used a digital scale (measuring range 0-3100 g and ±0.01g of uncertainty and resolution); that allows the recording of the mass - total and partials, the last ones retained in each opening of the sieves.

The bulk density (ρ_{Bulk}, kg.m^{-3}) was determined experimentally, taking as a reference to NBR 6922 (ABNT, 1981), the sample mass (m, kg) that fills a predefined container (v, m^3). The apparent density ($\rho_{Apparent}$, kg.m^{-3}) applies to a continuous substance such as leather-skin before industrial processing. Thus, it was not considered in the present study. However, ρ_{Bulk} better represents the sample condition after particle size uniformity and whose characteristics alike other fresh biomass or commercial ones (pellets and briquettes).

2.2 PROXIMATE AND ULTIMATE ANALYSES

For both, proximate and ultimate analysis, the sample mass was 1g and at least two repetitions in laboratory ambient conditions for $25\ °C \pm 5\ °C$. The other measuring equipment used are: Acculab ALC-210.4 analytical scale (± 0.001g for drying and AC_{db}), Bel Engineering M2202 centesimal scale (±0.01g for proximate analysis and ρ_{Bulk}), muffle oven (Fornitec 2.2 kW), ceramic crucibles and lids.

The sample should be dry long enough in a drying oven until there is no mass variation (scale, ± 0.001g), and it took 45 minutes for complete drying. The proximate analysis was obtained experimentally in duplicate, according to NBR 8112, although originally for charcoal (ABNT, 1986). It provides content for: moisture content on a wet (wb) and dry (db) basis (MC_{wb} and MC_{db}; $\Delta MC \leq 5\%$; particle size < 19 mm; 105 ± 5 °C), volatile matter (VM_{db}; $\Delta VM_{db} \leq 2\%$; 0.150mm $<$ particle size $<$ 0.210 mm; and temperature 900 ± 10 °C), ashes (AC_{db}; $\Delta AC_{db} \leq 10\%$; particle size $<$ 0.210 mm; and temperature 700 ± 10 °C) and fixed carbon on a dry basis (Fc_{db}). Eq. (1) presents the indirect determinations of Fc_{db}, through the difference between VM and AC (ABNT, 1986).

$$FC_{db}\,(\%) = 100 - [(VM_{db}\,(\%) + AC_{db}\,(\%)] \quad (1)$$

Ultimate analysis also known as chemical or elemental composition, consists in determining the weight ratio (WR, %) for carbon (C_{WR}), hydrogen (H_{WR}), nitrogen (N_{CR}), sulfur (S_{CR}), and oxygen (O_{WR}).

Experimental determination used a CHNS/O elemental analyzer with a 720s analysis cycle (Thermo Fisher Scientific, model Flash smart) and carrier gases at 140 $mL.min^{-1}$ (He) and 250 $mL.min^{-1}$ (O_2), consistent with NBR 8631 standards (ABNT, 1984a). The oxygen content (O_{WR}) was determined by the difference in dry weight ash-free basis, according to Eq. (2):

$$O_{WR} (\%) = 100 - [C_{WR} (\%) + H_{WR} (\%) + N_{WR} (\%) + S_{WR} (\%)] \quad (2)$$

2.3 HEATING VALUES AND ENERGY DENSITY

The high heating value (HHV, $kJ.kg^{-1}$), was measured experimentally, according to NBR 8633 (ABNT, 1984b) and determined using a bomb calorimeter (PARR, model 1341). HHV is the fuel´s chemical energy and corresponds to thermal energy (heat) released by combustion per mass unit. The low heating value (LHV, $kJ.kg^{-1}$), is determined by Eq. (3), and it depends on the moisture content in the fuel sample. Thus, corresponds to the HHV without energy from water condensation in combustion gases, i.e., the latent heat from hydrogen combustion.

$$LHV = HHV_{Experimental} - 2240 \, [\, (9 \, (H_{WR}) + MC_{wb}] \quad (3)$$

For comparison, the HHV is also determined via correlations, based on the experimental results from the ultimate analysis, (Rendeiro; Nogueira, 2008) in Eq. (4), and also based on experimental results from the proximate analysis (with valion for samples of diversified biomass (Parikh; Channiwala; Ghosal, 2005) that is determined by Eq. (5).

$$HHV = 0.4371 \, (C_{WR}) - 1.6694 \quad (4)$$
$$HHV = 0.3536 \, (FC_{db}) + 0.1559 \, (VM_{db}) - 0.0078 \, (Ac_{db}) \quad (5)$$

For transportation issues, costs mainly, it is relevant to know the volume occupied by a certain amount of energy in the solid biofuel. Thus, ρ_{Energy} ($MJ.m^{-3}$) plays the role as an "energy density" parameter, similar to HHV i.e., energy per volume instead of energy per weight; it is determined according to Eq. (6).

$$\rho_{Energy} \, (MJ.m^{-3}) = \rho_{Bulk} \, . \, HHV \quad (6)$$

3 RESULTS AND DISCUSSION

The first characteristic evaluated was the bulk density, that considers all particle sizes together, obtaining $\rho_{\text{Bulk equal to}}$ 110 $kg.m^{-3}$. It is a low value compared to typical biomass, about half of that sugarcane bagasse with 200 $kg.m^{-3}$ (Brand, 2010), then densification as pellets is an option to reach at least 400 $kg.m^{-3}$ (Kluska; Turzynski; Kardas, 2018). It turns LSW into a more competitive product considering logistics aspects for transportation and storage to become a commercial option. For biomass, usually particle size does not affect its HHV in biomass fuels (Heya *et al.*, 2022). But it interferes on densification properties, pellets or briquettes, once it depends on the density for fine or coarse particles; briquetting of larger particle size is possible, although both pelletization and briquetting are similar processes (Adekunle *et al.*, 2021). Also, as particle size increases the porosity of biomass pellets and briquettes may also increase (Hontsch *et al.*, 2024); however, finely comminuted material can improve the mechanical quality of briquettes.

In Figure 2, a logarithmic scale provides a better understanding of particle size distribution that has an exponential nature, allowing easier comparison and visualization for large values. The LSW particle size distribution demonstrates a weigh concentration of nearly 3/4 or 75% of the samples with an average particle diameter exceeding 4.75 mm. Another 25% or ¼ falls within the range of 0.85 and 1.70 mm. Due to the fact that 90% of these leather residues have an average particle diameter greater than 1.00 mm, they are classified as coarse particles (100-1000 μm or 0.1-1.0 mm). It points out another option for transport issues, as agglomeration to obtain granules for reuse and recycling in other technological processes.

Particle sizes in this work are adequate for pelletization, once briquetting is recommended if higher than 6 mm (Adekunle *et al*., 2021). For densification, the energy required in the process increases with increasing particle size, in comparison, to biomass particle size lower than unity and the same occur for sizes higher than unity (Hontsch *et al*., 2024). The particle size distribution of the present work is in line with the proposal to use it as solid biofuel, such as commercial pellets.

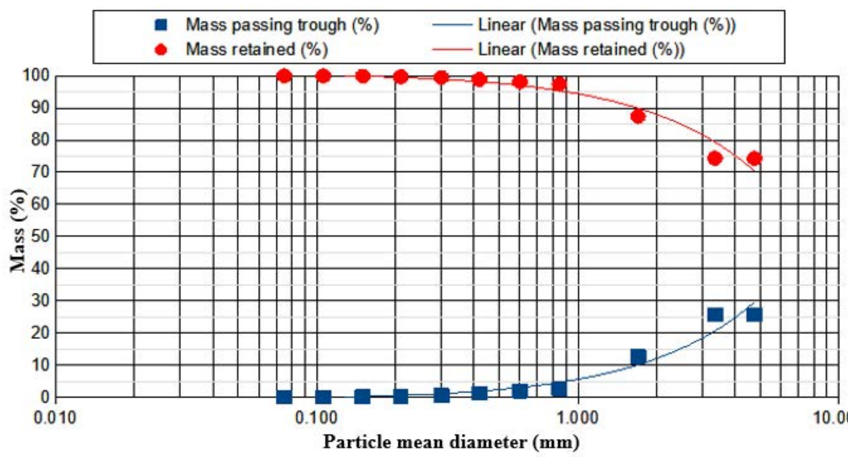

Figure 2. Leather solid waste particle size distribution for identification of mean diameter

Concerning the composition via proximate analysis, Figure 3 presents the respective dry basis ratios. MC_{wb} equals to 12% is within the limits, so there's no need for artificial drying if we're aiming for combustion. It has the same order of magnitude as some fresh plant-origin biomass (Rendeiro and Nogueira, 2008). Also, it is well below 35% humidity, the moisture value reached by residues in tanneries, whose process to obtain tanned leather is based on vegetable or mineral tannin (Kluska; Turzynski; Kardas, 2018; Kluska *et al*., 2020).

The VM result close to 76% proved to be a good reference for ignition and flame support characteristics. Although there are no results from combustion tests of this work, those are typical values for plant origin biomass (70% $<$ VM $<$ 80%). In comparison, LSW in tanneries the VM is close to 68% (Kluska; Turzynski; Kardas, 2018; Tatano *et al*., 2012) and in Municipal Solid Waste (MSW) it ranges from 62% $<$ VM $<$ 80% (Tang *et al*., 2015; Zhan *et al*., 2019); it varies according to the conditions found in the disposal.

The FC is 17%, similar to values found in rice husk and sugarcane bagasse, which are 17% and 15%, respectively (Cortez; Lora; Gómez, 2008); and equivalent to those of some leather samples in MSW (Kluska *et al*., 2020). FC value in this work also fall in the range between 11% and 22%, as found in other leather residue sources (Kluska *et al*., 2020; (Tatano *et al*., 2012). The ash content is high, AC_{db} = 7%. It may become an operational issue when used for combustion purposes in thermal equipment, similar to what occurs when using sugarcane bagasse whose AC is 12% (Brand, 2010). Nevertheless, further analysis must consider the ash composition that can worsen slag formation in steam boilers.

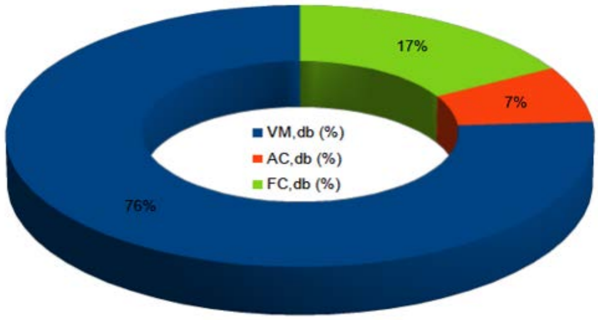

Figure 3. Leather solid waste proximate analysis: volatile matter (VM), ash (AC), and fixed carbon (FC) on a dry basis (db)

Table 1 indicates the H/C and O/C ratios, as well as the ultimate analysis, H, N, O, and C. The carbon corresponds to the content of volatile materials that separate from solid fuel. Another part of C_{WR} (fixed), next to the S_{WR} and AC_{db} (inorganic chemical elements), corresponds to the content attached in the solid part of the fuel. We notice that C_{WR}, H_{WR}, and O_{WR} amounts are equivalent to sugarcane bagasse, the most used residual biomass in Brazil (Brand, 2010; Rendeiro; Nogueira, 2008). Comparing these residues of the footwear industry and those of tanneries (Kluska; Turzynski; Kardas, 2018; Kluska *et al*., 2020), the fuel quality in the first is slightly better and requires less stoichiometric air ( ), that increases both C_{WR} and O_{WR} ( ). These characteristics differ significantly in leather residues typically found on MSW, especially with low N_{WR} ( ), indicating possible contamination by other MSW if mixing occurs or from different origins for these samples (Tang *et al*., 2015; Zhan *et al*., 2019).

As for N_{WR}, both leather residues from the footwear industry, or tanneries, present, quality values for use as an agricultural fertilizer in the soil - after removal of chromium and addition of potassium and calcium (Rizzato *et al*., 2020). As for the mass proportions for H/C and O/C, the first one is compatible with plant biomass that typically presents H/C lower than 0.2. Both, H/C and O/C, are equivalent to the proportions found for eucalyptus sawdust, respectively H/C = 0.13 and O/C = 0.87 (Silva *et al*., 2020). These characteristics corroborate the indication that leather residues can be used as solid fuel, just like other biomass of plant origin.

Table 1. Leather solid waste ultimate analysis, H/C, and O/C ratios, and literature comparison

Leather origin	C_{WR} (%)	H_{WR} (%)	N_{WR} (%)	S_{WR} (%)	O_{WR} (%)	Cl_{WR} [1] (%)	H/C (weight ratio)	O/C (weight ratio)
Footwear industry (1)	43.9	6.6	10.0	1.2	38.4	-	0.15	0.87
MSW leather (2)	47.5-61.9	4.4-7.0	1.4-2.4	0.7-2.4	19.3-44.3	~ 0.3	0.03-0.04	0.41-0.72
Tanning leather (3)	41.7	7.1	11.0	3.4	28.5	0.6	0.26	0.68

Note: C_{wr}, H_{wr}, N_{wr}, S_{wr}, Cl_{wr}: carbon, hidrogen, nitrogen, sulfur and chlorine content, respectively; H/C: hydrogen to carbon ratio; O/C: oxigen to carbon ratio; (1) from this work; (2) Municipal Solid Waste (MSW) leather (Tang *et al*., 2015); (3) Tanning leather (Kluska; Turzynski; Kardas, 2018; Kluska *et al*., 2020).

Figure 4 presents the results obtained for HHV and LHV, and comparison to literature for leather waste from other sources. LHV values are 8% lower than HHV, consistent with the definition of energy expended for water evaporation from samples. Correlations provide HHV on the same order of magnitude as the experimental one, with values 10% lower. HHV close to 20 $MJ.kg^{-1}$ for the LSW in this work is quite significant, superior to tannery leather which is 16-17 $MJ.kg^{-1}$ (Kluska *et al*., 2020; Tatano *et al*., 2012) and also compared to the biomass of agro-industrial origin (18 $MJ.kg^{-1}$, e.g., sugarcane bagasse), agricultural

(16 MJ.kg^{-1}, basically straw, leaves, and stems) and forestry (14 MJ.kg^{-1}, e.g., sawdust of wood, bark, chips, shavings, etc.) (Cortez; Lora; Gómez, 2008). The MSW leather has an HHV of almost 26 MJ.kg^{-1} (Zhan *et al.*, 2019), which may be due to its carbon content higher than other samples in the comparison (Table 1).

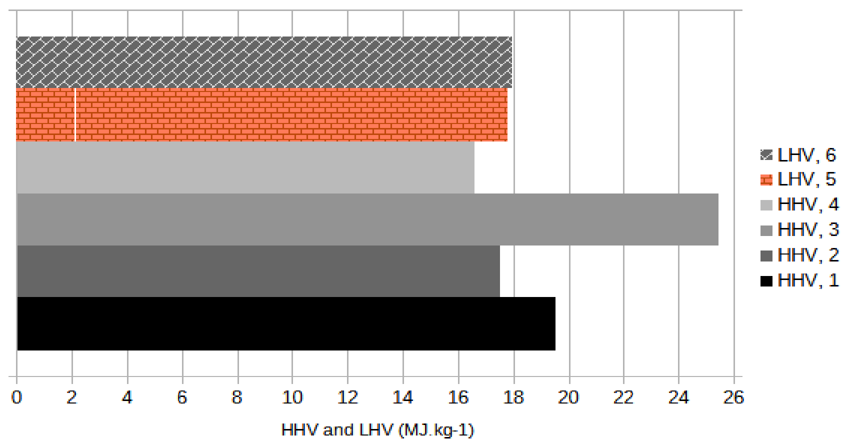

Figure 4. High heating value (HHV) and low heating value (LHV) for leather samples: 1 - Experimental; 2, 5, and 6 - Empirical correlations; 3 - MSW leather (Zhan *et al.*, 2019); 4 - Tanning leather (Kluska; Turzynski; Kardas, 2018; Kluska *et al.*, 2020).

Estimates by empirical correlation for typical footwear composed of leather, rubber, plastic, fabric, and wood, provide HHV equal to 21 MJ.kg^{-1} (Tippayawong, K.; Tippayawong, N., 2017), while an HHV ranging from 15.7-19.2 MJ.kg^{-1}, considering chrome tanned wastes (Velusamy *et al.*, 2020). Thus, the experimental HHV (19.51 MJ.kg^{-1}) obtained in the present work is consistent with literature and allows to indicate that LSW can provide relevant energy recovery as solid fuel.

As for energy density (ρ_{Energy} = 2.15 GJ.m^{-3}), it is a parameter mainly dependent on the bulk density. Our suggestion is to increase the ρ_{Bulk} in pellets by at least 4 (four) times to match another biomass that reach ρ_{Energy} of 10 GJ.m^{-3}. Consequently, both characteristics would enhance the competitiveness of the use of this solid fuel, from a technical and operational viewpoint.

In future works, we recommend other experimental tests to confirm the LSW feasibility for use as a commercial solid fuel, concerning emissions and pollutants, as well as chrome (Cr) removal before combustion.

4 FINAL CONSIDERATIONS

The bulk and energy density of LSW from the footwear industry are low (ρ_{Bulk} = 110 kg.m^{-3} and $\rho_{BEnergy}$ = 2 GJ.m^{-3}). A commercial solid fuel option could become more interesting by being densified for transport and storage purposes. The predominance of coarse particles (90% with a mean diameter higher than 1.00 mm) allows both pellets and briquettes densification.

The LSW analyzed here had characteristics that are similar to biomass, particulary in terms of VM_{db} (76%) and FC_{db} (17%), and for H/C and O/C ratios being in the same magnitude for *Eucalyptus* wood. The high ash content (AC_{db} = 7%) demands the same operational care in thermal equipment, as in sugarcane bagasse combustion (AC_{db} = 12%). MC_{wb} (12%) does not require artificial drying for combustion.

The HHV of 20 MJ.kg^{-1} is higher than that for typical biomass such as sugarcane bagasse or agricultural residues. Therefore, it can be concluded that the LSW investigated herein contains all essential attributes of a good quality solid fuel.

Results in this paper stimulates the use of LSW, and future works should investigate emission assessment to verify the permitted limits (e.g., chromium and chlorine), maybe requiring dilution/inflation of atmospheric air in combustion gases.

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REFERENCES

ASSOCIAÇÃO BRASILEIRA DE FUNDIÇÃO. **CEMP 081:** materiais para fundição: determinação da distribuição granulométrica, módulo de finura e teor de finos em materiais granulares: método de ensaio. São Paulo: ABIFA, 2015.

ASSOCIAÇÃO BRASILEIRA DAS INDÚSTRIAS DE CALÇADOS. **Relatório setorial**: Indústria de calçados do Brasil. Novo Hamburgo: ABICALÇADOS, 2024.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 6922**: carvão vegetal: determinação da massa específica (densidade a granel). Rio de Janeiro: ABNT, 1981.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 7402**: charcoal: granulometric determination: method of test. Rio de Janeiro: ABNT, 1982.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 8631**: carvão mineral: análise elementar: método de ensaio. Rio de Janeiro: ABNT, 1984a.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 8633**: carvão vegetal: determinação do poder calorífico. Rio de Janeiro: ABNT, 1984b.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 8112**: carvão vegetal: análise imediata. Rio de Janeiro: ABNT, 1986.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 10004**: resíduos sólidos: classificação. Rio de Janeiro: ABNT, 2004.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 3310-1**: peneiras de ensaio: requisitos técnicos e verificação, Parte 1: peneiras de ensaio com tela de tecido metálico. Rio de Janeiro: ABNT, 2010.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 14548**: couro: ensaios físicos e químicos: terminologia. Rio de Janeiro: ABNT, 2020.
ADEKUNLE, A.; ADELEKE, A. A.; ODUSOTE, J. K.; IKUBANNI, P. P.; LASODE, O. A.; MALATHI, M.; PASWAN, D.; Essential basics on biomass torrefaction, densification and utilization. **International Journal of**

Energy Research, v. 45, n. 3, p. 1375-1395, 2021. DOI: https://doi.org/10.1002/er.5884.
ALVES, V. C.; BARBOSA, A.S. Práticas de gestão ambiental das indústrias coureiras de Franca-SP. **Gest. Prod.**, v. 20, n. 4, p. 883-898, 2013. DOI: https://doi.org/10.1590/S0104-530X2013005000006.

ANGELI, J. R. B.; MORALES, A.; LeFLOC´h, T.; LAKEL, A.; ANDRES, Y. Anaerobic digestion and integration at urban scale: feedback and comparative case study. **Energy, Sustainability and Society**, v. 8, n. 29, p. 1-23, 2018. DOI: https://doi.org/10.1186/s13705-018-0170-3.

BRAND, M. A. **Energia da biomassa florestal**. 1.ed. Rio de Janeiro: Interciência, 2010.

BRASIL. Lei nº 12.305, de 2 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos; altera a Lei nº 9.605, de 12 de fevereiro de 1998; e dá outras providências. **Diário Oficial da União**, Brasília, DF, 3 ago. 2010.

BRASIL. Decreto nº 10.936, de 12 de janeiro de 2022. Regulamenta a Lei nº 12.305, de 2 de agosto de 2010, que institui a Política Nacional de Resíduos Sólidos. **Diário Oficial da União**, Brasília, DF, 12 jan. 2022.

CORRÊA, A. R. O complexo coureiro calçadista brasileiro. **BNDES Setorial**, v. 30, n. 14, p. 65-92, 2001.

CORTEZ, L. A. B.; LORA, E. E. S.; GÓMEZ, E. O. **Biomassa para energia**. 1. ed. Campinas: Editora da Unicamp, 2008.

DÁVILA-MARTINEZ, T. A.; SANCHEZ-PEÑA, N. E.; ORDOÑEZERAZO, D. A.; MUÑOZ-LÓPEZ, J. F.; BENITEZ-BENITEZ, R. Evaluation of agroindustrial waste as bio-filters: removal of Cr (vi) in tannery synthetic effluents (In Spanish). **Biotecnología en el Sector Agropecuario y Agroindustrial**, Ed. Especial, n.1, p. 49-58, 2017. http://dx.doi.org/10.18684/BSAA(Edición Especial)49-58.

HEYA, M. N.; HERNÁNDEZ. A. L. R.; POURNAVAB, R. F.; PINTOR, L. F. I.; DÍAZ-JIMÉNEZ, L.; HEYA, M. S.; CRUZ, L. R. S.; PARRA, A. C.; Physicochemical Characteristics of Biofuel Briquettes Made from Pecan (Carya illinoensis) Pericarp Wastes of Different Particle Sizes. **Molecules**, v. 27, n. 1035, 2022. DOI: https://doi.org/ 10.3390/molecules27031035.

HONTSCH, S.; FEHSE, F.; SCHRODER, H-W.; HERDEGEN, V.; BRAEUER, Q. S.; Influence of comminution and briquetting parameters on the agglomeration behaviour of wheat straw. **Biomass and Bioenergy**, v. 182, 107077, 2024. DOI: https://doi.org/10.1016/j.biombioe.2024.107077.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Pesquisa Agropecuária Municipal**. Brasília: IBGE, 2020.

JIANG, H.; LIU, J.; HAN, W. The status and developments of leather solid waste treatment: A mini-review. **Waste Management and Research**, v. 34, n. 5, p. 399-408, 2016. DOI: https://doi.org/10.1177/0734242X16633772.

KAVOURAS, P.; PANTAZOPOULOU, E.; VARITI, S.; VOURLIAS, G.; CHRISSAFIS, K.; DIMITRAKOPULOS, G. P.; MITRAKAS, M; ZOUBOULIS, A. I.; KARAKOSTAS, T.; XENIDIS, A. Incineration of tannery sludge under oxic and anoxic conditions: Study of chromium speciation, **Journal of Hazardous Material,** v. 283, p. 672-679, 2015. DOI: https://doi.org/10.1016/j.jhazmat.2014.09.066.

KLUSKA, J.; TURZYNSKI, T.; KARDAS, D. Experimental tests of co-combustion of pelletized leather tannery wastes and hardwood pellets. **Waste Management**, v. 79, p. 22-29, 2018. DOI: https://doi.org/10.1016/j.

wasman.2018.07.023
KLUSKA, J.; TURZYNSKI; OCHNIO, M.; KARDAS, D. Characteristics of ash formation in the process of combustion of pelletied leather tannery waste and hardwood pellets. **Renewable Energy**, v. 149, p. 1246-1253, 2020. DOI: https://doi.org/10.1016/j.renene.2019.10.122

LAZAROIU, G.; PANÃ, C.; MIHAESCU, L.; CERNAT, A.; NEGURESCU, N.; MOCANU, R.; NEGREANU, G. Solutions for energy recovery of animal waste from leather industry. **Energy Conversion and Management**., v.149, p.1085-1095, 2017. DOI: https://doi.org/10.1016/j.enconman.2017.06.042.

MA, H.; LI, X.; ZHU, C.; CHEN, F.; YANG, Y.; CHEN, X. Liberation and recovery of Cr from real tannery sludge by ultrasoundassisted supercritical water oxidation treatment. **Journal of Cleaner Production**, v. 267, n. 9, p. 340-344, 2020. DOI: https://doi.org/10.1016/j.jclepro.2020.122064.

NAÇÕES UNIDAS BRASIL. **Os objetivos de desenvolvimento sustentável no Brasil**. NU Brasil, 2025.

NUR-E-ALAM, M.; MIA, M. A. S.; AHMAD, F.; RAHMAN, M.M. An overview of chromium removal techniques from tannery effluent. **Applied Water Science**, v. 10, n. 9, 2020. DOI: https://doi.org/10.1007/s13201-020-01286-0.

PARIKH, J.; CHANNIWALA, S. A.; GHOSAL, G. K. A correlation for calculating HHV from proximate analysis of solid fuels. **Fuel**, v. 84, n. 5, p. 487-494, 2005. DOI: https://doi.org/10.1016/j.fuel.2004.10.010.

PEDDE, V.; FIGUEIREDO, J. A.; TUNDISI, J.G.; LENZ, C. A. The environmental risk as a culture in the Sinos Valley, **Brazil. An. Acad. Bras. Cienc**, v. 86, n. 4, p. 2145-2156, 2014. DOI: https://doi.org/10.1590/0001-3765201420130122.

POMPEI, S.; TIRILLO, J.; SARASINI, F.; SANTULLI, C. Development of thermoplastic starch (TPS) including leather waste fragments. **Polymers**, v. 12, n. 8, 2020. DOI: https://doi.org/10.3390/polym12081811.

RENDEIRO, G.; NOGUEIRA, M. F. M.; BRASIL, A. C. M.; CRUZ, D. O. A.; GUERRA, D. R. S.; MACÊDO, E. N.; ICHIHARA, J. A. **Combustão e gaseificação de biomassa sólida:** soluções energéticas para a Amazônia. 1.ed. Brasília: Ministério de Minas e Energia, 2008.

RIZZATO, M. P.; BERTO, L. K.; CORSO, M.; ALBUQUERQUE, A. C. D.; AZENHA, T. D.; REZENDE, L. C. S. H. Composites formed by recycled polypropylene and wet-blue leather waste: A sustainable practice. **Brazilian Journal of Environmental Sciences**, v. 55, n. 2, p. 256-267, 2020. DOI: https://doi.org/10.5327/Z2176-947820200654.

SILVA, R. L., PATELLI JR., J. R., SEYE, O., MICHELS, C. S., PAULA, I. O., SCHNEIDER, P. S. Experimental investigation on eucalyptus sawdust torrefaction for energy properties upgrading. **Scientia Forestalis**, v. 48, n. 125, p. e2931, 2020. DOI: https://doi.org/10.18671/scifor.v48n125.01.

SOUZA, R. S.; SANTOS, V. M.; MELO, W. J.; NUNES, L. A. P. L.; van den BRINK, P. J.; ARAÚJO, A. S. F. Time-dependent effect of composted tannery sludge on the chemical and microbial properties of soil. **Ecotoxicology**, v.2 6, n. 8, p. 1366-1377, 2017. DOI: https://doi.org/10.1007/s10646-017-1861-9.

TANG, Y. T.; MA, X. Q.; LAI, Z. Y.; FAN, Y. Thermogravimetric analyses of co-combustion of plastic, rubber, leather in N2/O2 and CO2/O2 atmospheres. **Energy**, v. 90 (part 1), p.1066-1074, 2015. DOI: https://doi.org/10.1016/j.energy.2015.08.015.

TATANO, F.; ACERBI, N.; MONTERUBBIANO, C.; PRETELLI, S.; TOMBARI, L.; MANGANI, F. Shoe

manufacturing wastes: Characterization of properties and recovery options. **Resources, Conservation and Recycling**, v. 66, p. 66-75, 2012. DOI: https://doi.org/10.1016/j.resconrec.2012.06.007.
TIPPAYAWONG, K. Y.; TIPPAYAWONG, N. Fuel recovery from thermal processing of post-consumer footwear waste. **Journal of Energ y Engineering**, v. 114, n. 3, p. 7–16, 2017). DOI: https://doi.org/10.1080/01998595.2017.11863761.

U.S. Bureau of Standard Notes. Heat of combustion of leather. **Journal of the Franklin Institute**, v. 210, n. 2, p. 253, 1930. DOI: https://doi.org/10.1016/S0016-0032(30)90752-1.

VELUSAMU, M.; CHAKALI, B.; GANESAN, S.; TINWALA, F.; VENKATACHALAM, S. S.; Investigation on pyrolysis and incineration of chrome-tanned solid waste from tanneries for effective treatment and disposal: an experimental study. Environmental science and pollution research international, v. 27, p. 29778–29790, 2020). DOI: https://doi.org/10.1007/s11356-019-07025-6.

ZATTERA, A. J.; BIANCHI, O.; ZENI, M.; FERREIRA, C. A. Characterization of ethylene-vinyl acetate copolymer (EVA) residues. **Polímeros**, v. 15, n. 1, p. 73-78, 2005. DOI: https://doi.org/10.1590/S0104-14282005000100016.

ZHAN, M.; SUN, C.; CHEN, T.; LI, X. Emission characteristics for co-combustion of leather wastes, sewage sludge, and coal in a laboratory-scale entrained flow tube furnace. **Environ. Sci. Pollut. Res.**, v. 26, p. 9707-9716, 2019. DOI: https://doi.org/10.1007/s11356-019-04347-3.