

Research Article

Development of Flexible Composite Sheet with Chrome Shavings Using Polyvinyl Alcohol as a Cross-Linker

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Leather processing generates a huge amount of chromium (Cr) containing wastes, and one of them is chrome shavings (CS), which frequently end up in landfills. It may be harmful to the environment and human health due to the oxidation of Cr(III) to poisonous Cr(VI). Herein, CS and polyvinyl alcohol (PVA) are used for the preparation of flexible CS-PVA composite sheets, using CS as a skeletal and PVA as a cross-linker by a simple and facile technique. CS-PVA composite sheets are characterized by FT-IR, SEM, STA, and UTM. FT-IR analysis of CS-PVA composite sheets indicated the existence of dominating peaks corresponding to collagen amide bands as well as PVA characteristic bands, and it demonstrates the uniformity of the developed composite sheets. When the amount of PVA is increased, the tensile strength of CS-PVA composite sheets increases from 0.21 to 4.17 N/mm². With increasing of the amount of PVA, the softness decreases from 6.47 to 3.7 mm, and SEM shows decreasing of pores in the composite sheet. The addition of more PVA makes CS-PVA composite sheets more thermally stable. This facile method of preparing CS-PVA composite sheet is low-cost and eco-friendly, having potential applications in various fields, including clothing, leather goods, decoration, packaging, and footwear products, as well as presenting promising platforms for effective utilization of industrial waste materials.

1. Introduction

Perishable hides and skins are transformed into stable leather in leather making process operated in a tannery. In Bangladesh, a huge amount of solid wastes generated during leather processing are dumped on land or river and cause critic environment and severe health problems [1]. One metric ton of raw hide generates about 200 kg of finished leather, 200-250 kg of tanned solid waste, and 200-350 kg of nontanned waste, and 100 kg is lost as wastewater [2, 3]. Solid waste from tannery comprises of 2-5% hair, 5-7% skin trimmings, 35-40% buffing dust, CS, chrome split, wet blue scraps, and 56-60% fleshing [4, 5]. These buffing dust, CS, and wet blue scraps contain a high quantity of chromium, whereas CS dust possesses 2.5-5% of chromium [6]. When these high chromium containing solid wastes are disposed of in landfills or other dumping sites, chromium may leach into the groundwater and affect the human food chain [7, 8].

Every year, 5.9×10^4 tons of hides and skins (bovine, sheep, lamb, goat, and kid) are used as raw materials for leather production in Bangladesh [9], resulting in massive amounts of solid waste being produced by the tanneries. Environmental pollution from the indiscreet dumping of solid waste generated by tanneries causes harmful consequences



Flexible composite sheet

FIGURE 1: Pictorial representation of the formation of CS-PVA composite sheet.

on human health [10]. Due to the production of solid, liquid, and gaseous pollutants, the Department of Environment (DoE) of Bangladesh has described tanneries as an industry under the "red" category [7]. However, several approaches have been proposed to manage the solid wastes emanating from the tanneries [11–15]. The solid wastes can be utilized by producing activated carbon [16], bioadsorbent [17], biodiesel [18], and biohydrogen [19]. Most importantly, collagen, glue, keratin, gelatin, etc. have been extracted from the solid wastes of the tannery for the preparation of composite leather board, composite material, poultry and fish feed, and functional materials for biomedical applications [15, 20–25].

One method of the various approaches for treating tannery solid wastes, including buffing dust and CS, is the fabrication of composites using polymers [24]. Due to the inherent fibrous nature of leather waste, it can be utilized as a reinforcing component in a variety of thermoplastic composite materials [26]. To get better compatibility with thermoplastic goods, some additives or modifying leather fibers, such as polyethylene, polypropylene, polyvinyl chloride (PVC), and polystyrene were added for in situ polymerization with other polymers, e.g., methyl methacrylate [27, 28]. PVA has good biodegradability, water solubility, nontoxicity, thermal stability, cross-linking ability, high mechanical properties, and noncorrosiveness [29, 30]. The chemical resistance and physical properties of PVA have contributed to its extensive industrial applications in numerous purposes, such as drug delivery [31], membrane separation system [32], packaging [33], tissue engineering [34], and hydrogels or microgels [35].

Composite sheets were prepared to combine leather waste and PVC [27, 36]. To improve the mechanical and thermal characteristics of thermoplastic polymer composite, leather wastes were employed as fillers in those materials [37]. Furthermore, compression molding of chemically processed short leather fibers into plasticized PVC matrix and dioctyl phthalate plastisols was used to produce composites with enhanced characteristics [38, 39]. Rajaram et al. prepared polymer composites using butadiene rubber, PVC, and CS, to have high machinability and nailing quali-



FIGURE 2: FT-IR spectra of PVA and CS-PVA composite sheets (the results were presented with respect to wt% of PVA in CS): (a) PVA 50%, (b) PVA 40%, (c) PVA 30%, (d) PVA 20%, (e) PVA 10%, (f) PVA 0%, and (g) PVA 100%.

ties [40]. In addition, collagen hydrolysate and PVA were utilized for biodegradable thermoplastic film fabrication where collagen hydrolysate came from enzymatically hydrolyzed CS in the presence of organic amines [41, 42].

To gain more profit and more employment facilities, as well as protect the environment, tannery waste materials need to be utilized properly. The present study mainly focused on the formulation of chrome shaving-polyvinyl alcohol (CS-PVA) composite sheets to be employed in clothing, regenerated leather, decoration field, key chain holder,



FIGURE 3: Possible cross-linking reactions between collagen in CS and PVA.

packaging, footwear products such as shoe soles and insole. The goal of this work is to fabricate flexible composite sheets from CS and PVA, an easily available water-soluble synthetic polymer with excellent mechanical properties, bio-compatibility, biodegradability, nontoxicity, and chemical resistance. PVA and CS were partially hydrolyzed by nitric acid, and then, CS-PVA composite sheets were prepared using various proportions of PVA and CS. The thermal, mechanical, and morphological properties of the prepared CS-PVA composite sheets were studied. Applying the criteria of "clean and green technology," this study presents an easy technology for solid tannery waste management.

2. Experimental

2.1. Materials. CS were obtained from tannery industry situated at Savar, Dhaka, Bangladesh. Then, the CS was washed, sun-dried, and preserved at room temperature in an airtight container. Polyvinyl alcohol (PVA) (degree of polymerization 1700-1800) was purchased from Research-Lab, India, and nitric acid was purchased from Merck Life Science Private Limited, India.

2.2. Partial Hydrolysis of CS. CS were grounded finely and separated into desired sizes (1 mm-2 mm) with the help of a sieve shaker and kept at room temperature in an air tight container. Nitric acid (2.5 M) was added to the known amount of CS at a ratio of 100% (v/w), and then, distilled water of 200% (v/w) was added. After gently stirring the mixture, it was left undisturbed for 30 mins. The previously mentioned mixture was heated in a water bath at 70°C for 20 mins with constant stirring and formed a viscous mass. The formed viscous composite precursor was left undisturbed for 30 mins. In this stage, the obtained viscous composite precursor of chrome shaving and nitric acid was denoted as CS.

2.3. Preparation of Composite Sheets. Partially, hydrolyzed CS was mixed with PVA using a mechanical stirrer in different weight ratios, such as 10, 20, 30, 40, and 50 wt% based on the weight of CS. The corresponding mixture of CS and PVA was heated for 10 mins at 60°C while being stirred. The formed viscous paste of CS-PVA was pressed in a compres-

sion molding machine with 50 kN pressure and 60°C for 60 mins. The CS-PVA sheet was demolded after cooling down at -18°C and then air dried at room temperature. As can be seen, this straightforward, highly effective, and environmentally friendly method can be used to develop flat and flexible CS-PVA composite sheets, as illustrated in Figure 1.

2.4. Characterization

2.4.1. Tensile Testing. In accordance with SATRA TM43 [43], tensile tests on CS-PVA composite sheets were carried out using a computer-controlled universal testing machine (UTM) (STM 566, United Kingdom) with a test speed of 100 mm/min and an extensometer gauge length of 50 mm. Each type of composite sheet was evaluated with three specimens that were 90 mm long and 10 mm wide, and the load cell was maintained at 1 kN. From the average of three individual measurements, the final mechanical characteristics of the composite sheets were presented.

2.4.2. FT-IR Spectroscopy. The infrared spectra of the CS, PVA and developed CS-PVA composite sheets, were obtained using a Fourier-transform infrared spectrophotometer (FT-IR) (Perkin-Elmer, Frontier, United Kingdom) with Universal Attenuated Total Reflectance Accessory (UATR). Absorbance and FT-IR spectra were recorded for each sample. Initially, the FT-IR spectrometer was calibrated for background scanning signal against a pure KBr sample. Each spectrum was acquired after an average of 20 scans with a resolution of 4 cm⁻¹ in the frequency bands 4000-600 cm⁻¹.

2.4.3. Scanning Electron Microscopy (SEM). The morphology of CS and CS-PVA composite sheets were examined using SEM. Micrographs of the surface were taken using a ZEISS AVO 18 (Carl Zeiss, Germany) research scanning electron microscope at 1500 times magnification and an accelerating voltage of 12 kV.

2.4.4. Simultaneous Thermal Analyzer (STA). STA (Model: 449 F3 Jupiter[®]; Brand: NETZSCH GmbH) was used to investigate the thermal stability of the composite sheets using Proteus software. Thermal properties of the composite sheets were measured from room temperature to 800°C in a nitrogen atmosphere, where the heating rate was 20°C/min.



FIGURE 4: TG curves of CS-PVA composite sheets (the results were presented with respect to wt% of PVA in CS): (a) PVA 100%, (b) PVA 0%, (c) PVA 10%, (d) PVA 20%, (e) PVA 30%, (f) 40%, and (g) PVA 50%.

Moreover, the same instrument was used for differential scanning calorimetry (DSC) measurement to examine the thermal characteristics of the developed composite sheets. For DSC measurement, a constant heating rate of 20°C/ min was maintained from room temperature to 300°C while nitrogen was present.

CS-PVA composition (wt%)	Softness (mm)	Load (N)	Tensile strength (N/mm ²)	Elongation (%)	Moisture content (%)
10	6.47	1.48	0.21	32.20	14.98
20	6.15	6.14	0.80	51.20	17.72
30	5.96	24.57	2.19	47.23	16.87
40	5.22	53.74	3.20	30.52	17.42
50	3.70	71.70	4.17	24.95	17.35

TABLE 1: Mechanical properties, softness, and moisture content of the CS-PVA composite sheets (here, CS-PVA compositions were presented with respect to wt% of PVA in CS).

2.4.5. Softness Tester. An ST 300 digital leather softness tester was used to assess the softness of composite sheets in accordance with the standard procedure [44]. The reducing ring utilized has a 10 mm diameter. Measuring the distension of composite sheets, the softness was expressed in mm.

2.4.6. High-Performance Moisture Analyzer. The moisture content of the CS and CS-PVA composite sheets was measured using a high-performance moisture analyzer (WBA-110 M). Required amount (1-2 g) of composite sheet samples were cut, and the moisture content was evaluated according to the ISO 287:2017 method.

3. Results and Discussion

3.1. FT-IR Analysis. Figure 2 shows the FT-IR spectra of composite sheets made of PVA and CS. The peaks of the amide I (1,700-1,600 cm⁻¹), amide II (1,600-1,500 cm⁻¹), and amide III (1,300-1,200 cm⁻¹) bands are typically used to represent the FT-IR spectra of proteins [45]. In the FT-IR spectra (Figure 2), CS with 0% PVA reveals collagen's distinctive peaks, including amide I at 1,633 cm⁻¹ for C=O stretching, amide II at 1,548 cm⁻¹ for N–H and C–N vibrations, and amide III at 1,237 cm⁻¹ for C-N stretching, N-H in plane bending, and absorptions arising from wagging vibrations from CH₂ groups. The short peaks around 2,986 and 2,882 cm⁻¹ are caused by the methylene groups for asymmetric stretching. The presence of amine and hydroxyl groups in the collagen molecule accounts for the broad peak reaching over 3300 cm⁻¹. The outcomes support the preceding reports in this case [27, 46]. The pure PVA pattern showed a sharp-edged peak at 1,090 cm⁻¹ corresponding to C-O stretching, two small peaks at 2,911 cm⁻¹ and 2,944 cm⁻¹ caused by the respective asymmetric and symmetric stretching vibration of methylene groups, and a broad peak at 3,308 cm⁻¹ caused by a strong O-H stretching vibration [47]. It is noteworthy to see that some of the distinctive peaks of both PVA and collagen may be seen in all CS-PVA composite sheets. As PVA concentration rises in the composite sheets, it is seen that the typical PVA peaks become more apparent. The dehydration of hydroxyl groups between PVA and CS resulted in the production of ether bonding (C-O-C), which was indicated by the prominent peak at 1,036 cm⁻¹. Additionally, the formation of ester bonding (-COO-), which was caused by the esterification reaction between the -OH in PVA and the -COOH in CS, was also shown by the second strong peak at around 1234 cm^{-1} .



FIGURE 5: DSC thermograms of CS-PVA composite sheets (the results were presented with respect to wt% of PVA in CS): (a) PVA 0%, (b) PVA 100%, (c) PVA 10%, (d) PVA 20%, (e) PVA 30%, (f) 40%, and (g) PVA 50%.

3.2. Design Concept of CS-PVA Composite Sheets. The majority (75–85%) of the CS are composed of collagenous protein [48]. Polypeptide chains, that makeup collagen, have repeating sequences of amino acids, and the most prevalent sequence is glycine-proline-hydroxyproline (Gly-Pro-Hyp) [49]. Here, condensation reaction may be occurred between PVA and CS [50].

Figure 3 depicts the relevant and possible chemical reaction between CS and PVA. These findings show that PVA was homogeneously mixed and incorporated into the CS mass.

3.3. Thermogravimetry (TG) Analysis. TG was used for determining the thermal degradation properties of PVA and CS-PVA composite sheets, and the resulting thermograms are displayed in Figure 4. PVA undergoes decomposition in a single step, with an inflection point at 288°C. This point corresponds to the decomposition of the polymer matrix, and the mass change that occurs is approximately 74%. The weight loss in all of the CS-PVA composite sheets occurs in two stages, and this is well agreed with the literature [51, 52]. Due to the evaporation of moisture content, the initial stage of mass loss for all CS-PVA composite sheets occurs between 80 and 120°C. The resulting weight loss is roughly 9-15%, which agrees with the moisture content analysis in Table 1. In the second step, mass loss occurs



FIGURE 6: SEM images of CS-PVA composite sheets at a magnification of 1500 times (the results were presented with respect to wt% of PVA in CS): (a) PVA 0%, (b) PVA 10%, (c) PVA 20%, (d) PVA 30%, (e) PVA 40%, and (f) PVA 50%.

between 200 and 480°C, and it may be attributed to the breakdown of the PVA-collagen cross-linking. The denaturation temperature of composite sheets rises progressively from 316° C (PVA/CS 0 wt%) to a maximum of 326° C (PVA/CS 50 wt%). The outcomes here agree with those of the tensile strength, SEM, and DSC analyses. The decomposition of CS-PVA composite sheets results in a mass change of 33-41%.

3.4. Differential Scanning Calorimetric (DSC) Analysis. DSC was used to study the thermal characteristics of PVA and CS-PVA composite sheets, and the findings are depicted in Figure 5. The pure PVA DSC thermogram clearly showed a significant melting endothermic peak at 222.9°C [53].

Here, the PVA/CS 0% composite sheet did not exhibit a peak around 200°C. Strong chemical interaction between PVA and CS would alter the properties of pure PVA, and this is clearly seen in the composite sheets that the endothermic peaks are not only weaker and broader but also moved to lower temperatures [50].

3.5. Scanning Electron Microscopic (SEM) Analysis. At a magnification of 1500 times, Figure 6 depicts SEM images of the developed CS-PVA composite sheets. The SEM image of CS showed that CS had lots of microvoids and porosity, which may be helpful for the cross-linking with PVA (Figure 6(a)). On the other hand, there were uneven surfaces and many voids in the composite sheet with 10 wt% PVA

content (Figure 6(b)), which may be caused by weak PVAcollagen binding. The voids in the composite sheets gradually decreased with the increasing of PVA percentage from 20% to 40% (Figures 6(c)–6(e)). Finally, the CS-PVA composite sheet with a 50% PVA content, shown in Figure 6(f), displayed greater surface regularity and included fewer voids. As a result, it can be seen that in the developed CS-PVA composite sheets, the surface uniformity increases, and the presence of voids diminishes as the percentage of PVA increases from 10 to 50 wt%. This could be explained by the significant interfacial adhesion of PVA with the CS as PVA percentage increases.

3.6. Mechanical and Bulk Properties. Table 1 displays the mechanical characteristics of the developed CS-PVA composite sheets. As the PVA content in the CS-PVA composite sheets rises from 10 to 50 wt%, it can be seen that the mechanical properties of the composite sheets gradually improve. Comparing all the other sheets, the composite sheet with a 50 wt% PVA/CS composition has the best mechanical properties with regard to both load at break and tensile strength. SEM study of CS-PVA composite sheets with lower PVA percentages (10, 20, and 30% wt%) showed that there were more voids in those sheets, and this may be the main reason why the mechanical properties of those sheets were lower. In contrast, SEM research reveals that the CS-PVA composite sheets with 40 and 50 wt% PVA percentages have fewer voids, which helps to improve mechanical properties by increasing the binding between PVA and collagen matrix. As a function of the PVA content, the percentage elongation of CS-PVA composite sheets alters considerably. As the PVA percentage rose, it was discovered that the mechanical properties of the created composite sheets had improved. This is in good agreement with earlier research [51]. All of the CS-PVA composite sheets are found to be around 1.0 mm thick. All of the prepared sheets had a moisture content of about 16%, which is mostly attributable to the hydrophilic characteristics of collagen molecules. This is in accordance with the weight loss attributed to moisture evaporation that was found during the TGA analysis. The softness of composite materials intended for low-stress applications is an important aspect. High values of softness indicate that the material yields readily to pressure or weight, allowing it to be easily shaped, cut, or modified. Table 1 displays the softness values of developed CS-PVA composite sheets. As the percentage of PVA is increased, it can be noticed that the softness of the composite sheets diminishes. When compared to sheets with PVA/CS 50 wt% composition, the sheet with PVA/CS 10 wt% composition demonstrates superior softness and flexibility [51]. Here, the inverse relationship between softness and tensile stress is interesting to note. By adjusting the ratio of chromium shaving to PVA, it is now able to create CS-PVA composite sheets with the necessary strength and softness.

4. Conclusion

The current work proposed a feasible strategy for the management of chrome containing leather wastes, CS, produced

from the leather production sectors. Herein, flexible composite sheets comprised of PVA and CS were developed using a straightforward, simple, and effective method that required less chemical or effort. In this experiment, the tensile strength and thermal stability of the sheets increased as the PVA contain increases, whereas softness reduced considerably. With the increase of the amount of PVA in CS from 10 to 50 wt%, tensile strength was found 0.21 N/mm² to 4.17 N/mm², respectively. Similarly, the softness of the CS-PVA sheets was changed from 6.47 to 3.70 mm, respectively. Moreover, the denaturation temperature of composite sheets rises progressively from 316°C (PVA/CS 0 wt%) to a maximum of 326°C (PVA/CS 50 wt%). The results of the mechanical property analysis were strongly supported by scanning electron micrographs by showing fewer voids in composite sheets when the amount of PVA was increased. The etherification reaction and esterification reaction between CS and PVA were confirmed by the FT-IR spectra of the CS-PVA composite sheet. These findings show that composite sheets made of CS and PVA have good mechanical and thermal properties, making it possible to develop this simple and inexpensive composite for footwear, leather goods, and home interior applications. Additionally, the developed composites offer a solution to the environmental problems related to waste management in the leather industry.

Data Availability

All data presented or analyzed during this study are included in this article.

Conflicts of 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.

Authors' Contributions

Akash Debnath conducted the conceptualization, investigation, formal analysis, methodology, and writing of the original draft; Md. Ashraful Alam performed the data curation and formal analysis; Ajoy Kanti Mondal reviewed, edited, and wrote the paper; Md. Tushar Uddin reviewed, edited, and wrote the paper; Md. Aftab Ali Shaikh reviewed, edited, and validated the paper; S. M. Asaduzzaman Sujan supervised, validated, reviewed, and conducted the project administration and fund acquisition. All authors have read and agreed to publish the manuscript.

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References

- M. A. Moktadir and M. M. Rahman, "Energy production from leather solid wastes by anaerobic digestion: a critical review," *Renewable and Sustainable Energy Reviews*, vol. 161, article 112378, 2022.
- [2] C. B. Agustini, M. da Costa, and M. Gutterres, "Biogas from tannery solid waste anaerobic digestion is driven by the association of the bacterial order bacteroidales and archaeal family methanosaetaceae," *Applied Biochemistry and Biotechnology*, vol. 192, no. 2, pp. 482–493, 2020.
- [3] V. K. Kumar, R. Mahendiran, P. Subramanian, S. Karthikeyan, and A. Surendrakumar, "Optimization of inoculum to substrate ratio for enhanced methane yield from leather fleshings in a batch study," *Journal of the Indian Chemical Society*, vol. 99, no. 3, article 100384, 2022.
- [4] M. Ayele, D. Y. Limeneh, T. Tesfaye et al., "A review on utilization routes of the leather industry biomass," *Advances in Materials Science and Engineering*, vol. 2021, Article ID 1503524, 15 pages, 2021.
- [5] M. Uddin, M. Hasan, M. Islam, A. Rahaman, and S. M. Shamsuddin, "Removal of chromium (III) and other physical parameters from chrome tan wastewater and recovery of chromium from the precipitating sludge," *Textile & Leather Review*, vol. 3, no. 2, pp. 64–77, 2020.
- [6] A. Rahaman, M. R. Hosen, K. Bashar, J. S. Afroze, and U. Naher, "Extraction of chromium from leather chrome shaving dust," *International Journal of Scientific & Technology Research*, vol. 5, no. 10, pp. 160–163, 2016.
- [7] S. Ahmed, M. S. H. Fatema-Tuj-Zohra, and M. A. H. Khan, "Chromium from tannery waste in poultry feed: a potential cradle to transport human food chain, Cogent Environmental," *Science*, vol. 3, no. 1, article 1312767, 2017.
- [8] U. Anand, B. Reddy, V. K. Singh et al., "Potential environmental and human health risks caused by antibiotic-resistant bacteria (ARB), antibiotic resistance genes (ARGs) and emerging contaminants (ECs) from municipal solid waste (MSW) landfill," *Antibiotics*, vol. 10, no. 4, p. 374, 2021.
- [9] M. S. Hossen, Accumulation of Chromium from Feed to Different Edible Organs of Broiler, Chattogram Veterinary and Animal Sciences University Chattogram-4225, Bangladesh, 2018.
- [10] N. J. Alghamdi, E. M. Alhatimi, E. S. Alamri, A. O. B. Afif, W. A. Majrashi, and E. N. Danial, "Cytotoxicity and bioremediation of heavy metals by highly resistant marine bacteria," *Journal of Advances in Biology & Biotechnology*, vol. 24, no. 4, pp. 48–72, 2021.
- [11] M. R. Shaibur, "Heavy metals in chrome-tanned shaving of the tannery industry are a potential hazard to the environment of Bangladesh," *Case Studies in Chemical and Environmental Engineering*, vol. 7, article 100281, 2023.
- [12] B. Mella, J. Benvenuti, R. F. Oliveira, and M. Gutterres, "Preparation and characterization of activated carbon produced from tannery solid waste applied for tannery wastewater treat-

ment," *Environmental Science and Pollution Research*, vol. 26, no. 7, pp. 6811–6817, 2019.

- [13] A. Monga, A. B. Fulke, and D. Dasgupta, "Recent developments in essentiality of trivalent chromium and toxicity of hexavalent chromium: implications on human health and remediation strategies," *Advances*, vol. 7, article 100113, 2022.
- [14] Y. Tang, J. Zhao, Y. Zhang, J. Zhou, and B. Shi, "Conversion of tannery solid waste to an adsorbent for high-efficiency dye removal from tannery wastewater: a road to circular utilization," *Chemosphere*, vol. 263, article 127987, 2021.
- [15] Y. Li, R. Guo, W. Lu, and D. Zhu, "Research progress on resource utilization of leather solid waste," *Journal of Leather Science and Engineering*, vol. 1, no. 1, pp. 1–17, 2019.
- [16] J. Song, L. Yun, W. Yang et al., "Preparing biochars from cow hair waste produced in a tannery for dye wastewater treatment," *Materials*, vol. 14, no. 7, article 1690, 2021.
- [17] K. Song, H. Xu, L. Xu, K. Xie, and Y. Yang, "Cellulose nanocrystal-reinforced keratin bioadsorbent for effective removal of dyes from aqueous solution," *Bioresource Technol*ogy, vol. 232, pp. 254–262, 2017.
- [18] K. Devaraj, S. Aathika, Y. Mani et al., "Experimental investigation on cleaner process of enhanced fat-oil extraction from alkaline leather fleshing waste," *Journal of Cleaner Production*, vol. 175, pp. 1–7, 2018.
- [19] A. R. Salma Aathika, D. Kubendran, M. Yuvarani et al., "Enhanced biohydrogen production from leather fleshing waste co-digested with tannery treatment plant sludge using anaerobic hydrogenic batch reactor," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 40, no. 5, pp. 586–593, 2018.
- [20] C. V. T. Rigueto, M. Rosseto, D. D. C. Krein et al., "Alternative uses for tannery wastes: a review of environmental, sustainability, and science," *Journal of Leather Science and Engineering*, vol. 2, pp. 1–20, 2020.
- [21] H. Pu, C. Shu, R. Dai, H. Chen, and Z. Shan, "Mechanical, thermal and acoustical characteristics of composite board kneaded by leather fiber and semi-liquefied bamboo," *Construction and Building Materials*, vol. 340, article 127702, 2022.
- [22] D. Masilamani, B. Madhan, G. Shanmugam, S. Palanivel, and B. Narayan, "Extraction of collagen from raw trimming wastes of tannery: a waste to wealth approach," *Journal of Cleaner Production*, vol. 113, pp. 338–344, 2016.
- [23] Q. Xu, J. E. Torres, M. Hakim et al., "Collagen- and hyaluronic acid-based hydrogels and their biomedical applications," *Materials Science and Engineering: R: Reports*, vol. 146, article 100641, 2021.
- [24] V. Sivakumar and R. Mohan, "Sustainable solid waste management in leather and textile industry: leather & textile waste fibre-polymer composite and nanocomposite-overview and review," *Textile & Leather Review*, vol. 3, no. 2, pp. 54–63, 2020.
- [25] J. A. Claudio-Rizo, N. G. Hernandez-Hernandez, L. F. Cano-Salazar et al., "Novel semi-interpenetrated networks based on collagen-polyurethane-polysaccharides in hydrogel state for biomedical applications," *Journal of Applied Polymer Science*, vol. 138, no. 4, article 49739, 2021.
- [26] M. J. Ferreira and M. F. Almeida, "Recycling of leather waste containing chromium-a review," *Materials Science Research Journal*, vol. 5, no. 4, p. 327, 2011.
- [27] T. Madera-Santana, M. Aguilar-Vega, A. Márquez-Lucero, and F. Vázquez-Moreno, "Production of leather-like composites

using chemically modified short leather fibers. I: chemical modification by emulsion polymerization," *Polymer Composites*, vol. 23, no. 1, pp. 49–60, 2002.

- [28] T. J. Madera-Santana, M. Aguilar-Vega, A. Marquez, F. Vazquez Moreno, M. Richardson, and J. Cruz Machin, "Production of leather-like composites using short leather fibers. II. Mechanical characterization," *Polymer Composites*, vol. 23, no. 6, pp. 991–1002, 2002.
- [29] L. Li, X. Xu, L. Liu et al., "Water governs the mechanical properties of poly(vinyl alcohol)," *Polymer*, vol. 213, article 123330, 2021.
- [30] M. Sun, Y. Wang, L. Yao, Y. Li, Y. Weng, and D. Qiu, "Fabrication and characterization of gelatin/polyvinyl alcohol composite scaffold," *Polymers*, vol. 14, no. 7, p. 1400, 2022.
- [31] J. Li, P. Zhang, L. Chen et al., "Strong, tough and healable elastomer nanocomposites enabled by a hydrogen- bonded supramolecular network," *Composites Communications*, vol. 22, article 100530, 2020.
- [32] C. Wu and W. Xu, "Atomistic simulation study of absorbed water influence on structure and properties of crosslinked epoxy resin," *Polymer*, vol. 48, no. 18, pp. 5440–5448, 2007.
- [33] C. Wu, "Cooperative behavior of poly(vinyl alcohol) and water as revealed by molecular dynamics simulations," *Polymer*, vol. 51, no. 19, pp. 4452–4460, 2010.
- [34] K. S. Anseth, A. T. Metters, S. J. Bryant, P. J. Martens, J. H. Elisseeff, and C. N. Bowman, "In situ forming degradable networks and their application in tissue engineering and drug delivery," *Journal of Controlled Release*, vol. 78, no. 1-3, pp. 199–209, 2002.
- [35] Q. Wang, J. Gao, S. Liu, Y. Wang, and L. Wu, "Lignin nanoparticle reinforced multifunctional polyvinyl alcohol/polyurethane composite hydrogel with excellent mechanical, UVblocking, rheological and thermal properties," UV-blocking, rheological and thermal properties, International Journal of Biological Macromolecules, vol. 232, article 123338, 2023.
- [36] T. J. Madera-Santana, A. C. Torres, and A. M. Lucero, "Extrusion and mechanical characterization of PVC-leather fiber composites," *Polymer Composites*, vol. 19, no. 4, pp. 431–439, 1998.
- [37] B. Ramaraj, "Mechanical and thermal properties of ABS and leather waste composites," *Journal of Applied Polymer Science*, vol. 101, no. 5, pp. 3062–3066, 2006.
- [38] A. Andreopoulos and P. Tarantili, "Waste leather particles as a filler for poly (vinyl chloride) plastisols," *Journal of Macromolecular Science, Part A*, vol. 37, no. 11, pp. 1353–1362, 2000.
- [39] K. Babanas, P. Tarantili, and A. Andreopoulos, "Plasticized poly (vinyl chloride) filled with waste leather particles," *Journal of Elastomers & Plastics*, vol. 33, no. 1, pp. 72–85, 2001.
- [40] J. Rajaram, B. Rajnikanth, and A. Gnanamani, "Preparation, characterization and application of leather particulatepolymer composites (LPPCs)," *Journal of Polymers and the Environment*, vol. 17, no. 3, pp. 181–186, 2009.
- [41] P. Alexy, D. Bakoš, G. Crkoňová et al., "Poly (vinyl alcohol)– collagen hydrolysate thermoplastic blends: II. Water penetration and biodegradability of melt extruded films," *Polymer Testing*, vol. 22, no. 7, pp. 811–818, 2003.
- [42] Jaromír Hoffmann, I. Řezníčková, J. Kozáková et al., "Assessing biodegradability of plastics based on poly(vinyl alcohol) and protein wastes," *Polymer Degradation and Stability*, vol. 79, no. 3, pp. 511–519, 2003.

- [43] S. N. Jaisankar, S. Ramalingam, H. Subramani et al., "Cloisiteg-methacrylic acid copolymer nanocomposites by graft from method for leather processing," *Industrial & Engineering Chemistry Research*, vol. 52, no. 4, pp. 1379–1387, 2013.
- [44] "IUP 36 Measurement of leather softness," *Journal of the Society of Leather Technologists and Chemists*, vol. 84, pp. 377–379, 2000.
- [45] J. Andrade, C. G. Pereira, T. Ranquine, C. A. Azarias, M. J. V. Bell, and V. de Carvalho dos Anjos, "Long-term ripening evaluation of ewes' cheeses by Fourier-transformed infrared spectroscopy under real industrial conditions," *Journal of Spectroscopy*, vol. 2018, Article ID 1381864, 9 pages, 2018.
- [46] L. C. Oliveira, M. Goncalves, D. Q. Oliveira, M. C. Guerreiro, L. R. Guilherme, and R. M. Dallago, "Solid waste from leather industry as adsorbent of organic dyes in aqueous- medium," *Journal of Hazardous Materials*, vol. 141, no. 1, pp. 344–347, 2007.
- [47] L. Yang, H. Y. Zhang, Q. Yang, and D. N. Lu, "Bacterial cellulose-poly(vinyl alcohol) nanocomposite hydrogels prepared by chemical crosslinking," *Journal of Applied Polymer Science*, vol. 126, no. S1, pp. E245–E251, 2012.
- [48] C. Shanthi, P. Banerjee, N. C. Babu, and G. Rajakumar, "Recovery and characterization of protein hydrolysate from chrome shavings by microbial degradation," *Journal of the American Leather Chemists Association*, vol. 108, no. 6, pp. 231–239, 2013.
- [49] A. Owczarzy, R. Kurasiński, K. Kulig, W. Rogóż, A. Szkudlarek, and M. Maciążek-Jurczyk, "Collagen-structure, properties and application," *Engineering of Biomaterials*, vol. 23, no. 156, 2020.
- [50] C. Li, X. Feng, and E. Ding, "Preparation, properties, and characterization of novel fine leather fibers/polyvinyl alcohol composites," *Polymer Composites*, vol. 36, no. 7, pp. 1186–1194, 2015.
- [51] M. Ashokkumar, P. Thanikaivelan, K. Krishnaraj, and B. Chandrasekaran, "Transforming chromium containing collagen wastes into flexible composite sheets using cellulose derivatives: structural, thermal, and mechanical investigations," *Polymer Composites*, vol. 32, no. 6, pp. 1009–1017, 2011.
- [52] M. Ashokkumar, P. Thanikaivelan, R. Murali, and B. Chandrasekaran, "Preparation and characterization of composite sheets from collagenous and chromium-collagen complex wastes using polyvinylpyrrolidone: two problems, one solution," *Waste and Biomass Valorization*, vol. 1, no. 3, pp. 347–355, 2010.
- [53] T. Siddaiah, P. Ojha, N. O. Kumar, and C. Ramu, "Structural, optical and thermal characterizations of PVA/MAA: EA polyblend films," *Materials Research*, vol. 21, no. 5, 2018.