

Utilization of sugar beet pulp as an agricultural by-product in vegan leather production

A. Menekse, B. K. Isik, N. Tugrul*

Yıldız Technical University, Faculty of Chemistry and Metallurgy, Department of Chemical Engineering, Davutpaşa Campus, 34220 Esenler, Istanbul, Türkiye.

Accepted: July 28, 2026

The ecological degradation from traditional chrome-tanning and synthetic leathers necessitates biodegradable alternatives within polymer science and sustainable development frameworks. This study focuses on the valorization of sugar beet pulp (SBP), an abundant Turkish agro-industrial by-product, as a lignocellulosic matrix component for high-performance vegan leathers. SBP fibers were integrated into a starch/sodium alginate polymeric network and transformed into flexible vegan leathers *via* solution-casting. The fabricated leathers were characterized using Fourier transform infrared spectroscopy (FT-IR), tensile strength, water vapor transmission rate (WVTR), and water solubility analyses. Findings demonstrated that plasticizer selection and formulation parameters decisively influence matrix morphology, structural integrity, and barrier properties. FT-IR confirmed characteristic hydroxyl and polysaccharide-derived functional groups, proving molecular compatibility and stable cross-linking. The sorbitol-modified SBP4-So sample exhibited superior mechanical performance with a tensile strength of 22.26 MPa and a Young's modulus of 1374.22 MPa, making it competitive with traditional leather. Regarding barrier properties, the SBP4-AG sample optimized breathability and moisture management, yielding a minimized WVP of 1.15 g/m²·h. Furthermore, a minimum water solubility of 31% (SBP6-G) proved structural stability in aqueous environments. In conclusion, sugar beet pulp can be effectively engineered as a mechanically durable, eco-friendly, functional, and competitive leather alternative, offering a scalable innovation model aligned with circular economy principles.

Keywords: Vegan leather; sugar beet pulp; bio-material; biodegradable; sustainable

INTRODUCTION

The global leather industry is currently navigating a period of significant transformation driven by escalating environmental and ethical concerns. Traditional animal-based leather production is inherently resource-intensive, requiring vast grazing lands and contributing to high greenhouse gas emissions [1]. Moreover, the conventional tanning process relies heavily on chromium salts and consumes an average of 50 million m³ of water annually in regions like Türkiye, posing severe risks to aquatic ecosystems and human health when inadequately treated [2]. As an alternative, synthetic leathers based on petroleum-derived polymers such as polyvinyl chloride (PVC) and polyurethane (PU) have gained market share due to lower cost and scalability. However, these materials increase dependence on non-renewable fossil fuels and raise sustainability issues, as their low biodegradability leads to long-term environmental persistence and microplastic pollution [3]. These drawbacks have catalyzed a global demand for biodegradable "vegan leather" alternatives within polymer science and sustainable frameworks that mimic the aesthetic and functional properties of animal leather without the associated

environmental footprint [4-8]. Recent innovations have introduced diverse plant-based alternatives, including mycelium-based Mylo™, cactus-derived Desserto®, and pineapple leaf-based Piñatex [9-12]. Despite their potential, many require complex growth cycles or synthetic coatings to achieve durability, leaving a critical need for leather alternatives derived from abundant, low-cost agricultural by-products with minimal chemical modification. Türkiye, as a major producer of sugar beets, generates approximately 1.5 million tons of sugar beet pulp (SBP) annually [13]. Currently utilized primarily as low-value animal feed, SBP is a lignocellulosic biomass rich in cellulose (~25%), hemicellulose (~30%), and pectin (~22%) [14], making it a highly promising matrix for various biocomposite applications [15]. Its high pectin content is particularly advantageous, as it can form cross-linked gel structures that serve as a natural binder, potentially reducing the need for synthetic additives [16].

The objective of this study is to investigate the direct utilization of SBP powder as a primary matrix for the synthesis of sustainable, biodegradable, and high-performance vegan leathers. By employing a solvent-casting method with natural binders like starch and sodium alginate, and eco-friendly

* To whom all correspondence should be sent:

E-mail: ntugrul@yildiz.edu.tr

plasticizers such as glycerol and sorbitol, this research evaluates the mechanical and chemical characteristics of SBP-based vegan leathers. This approach addresses waste management challenges in the sugar industry while proposing a low-energy production model that consumes significantly less water and energy compared to traditional leather manufacturing.

EXPERIMENTAL

Materials

The primary raw material, sugar beet pulp (SBP), was obtained as a byproduct from the Alpulu Sugar Factory (Lüleburgaz, Türkiye) in February 2025. Natural additives used to enhance the structural properties included starch (ZAG Kimya), sodium alginate (Alfasol). Plasticization was achieved using glycerol (Sigma-Aldrich, PEG600), sorbitol (ZAG Kimya). Distilled water was utilized as the solvent phase for all formulations.

Preparation and standardization of SBP powder

To prepare the SBP for vegan leathers production, the wet pulp was first weighed into 200 g portions and dried in an oven (Ecocell) at 60°C for 48 h. The moisture content of the dried pulp was determined to be 14.6% based on the weight difference. Subsequently, the dried biomass was mechanically ground and sieved to achieve a uniform particle size of 250 µm. The resulting SBP powders were stored in a desiccator at room temperature (22±0.5°C) to maintain their stability and prevent moisture absorption.

Production of SBP-based vegan leathers

SBP-based vegan leathers were synthesized using a standardized solvent casting technique, with formulations optimized on a dry weight basis. SBP served as the primary structural matrix, ranging from 15.4% to 42.9% of the total dry weight. To ensure structural integrity and leather-forming characteristics, natural binders (starch and sodium alginate) were incorporated according to the ratios specified in Table 1, each constituting between 12.5% and 30.8% of the formulation's dry mass.

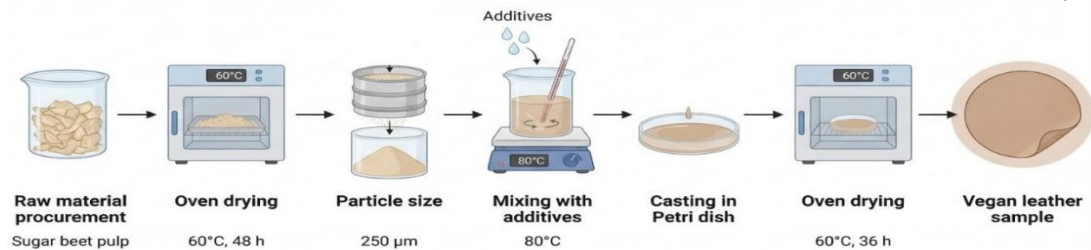


Figure 1. Schematic representation of the fabrication process of SBP-based vegan leather

Table 1. Detailed formulations and component ratios of the SBP-based vegan leather

Sample	SBP (g)	Starch (g)	Sodium alginate (g)	Glycerol (mL)	Sorbitol (g)	Additive* (wt%)	Plasticizer* (wt%)
SBP6-G	6	2	2	6	-	34.2	43.1
SBP4-G1	4	4	4	6	-	20.5	38.7
SBP4-SG	4	4	2	6	-	22.8	43.1
SBP4-AG	4	2	4	6	-	22.8	43.1
SBP6-SoG	6	2	2	3	3	35.7	40.4
SBP4-G2	4	2	2	6	-	25.7	48.6
SBP4-G3	4	2	2	8	-	22.1	55.7
SBP4-So	4	2	2	-	3	36.4	27.3
SBP2-G	2	2	2	6	-	14.7	55.8
SBP2-SG	2	4	2	6	-	12.8	48.6
SBP2-AG	2	2	4	6	-	12.8	48.6

*All weight percentages (wt%) for additives and plasticizers are calculated relative to the total solid weight of the formulation (total solids = starch + sodium alginate + SBP + plasticizer weight (glycerol + sorbitol)). Glycerol density was taken as 1.26 g/mL.

The fabrication process began with preparing a homogeneous hydrogel, where a predetermined amount of sodium alginate was dissolved in 250 mL of distilled water under constant stirring (500–900 rpm) at 80°C for 10–15 min. Starch and plasticizers, comprising 18.8% to 46.2% of the dry weight, were then integrated into the hydrogel matrix. Finally, the pre-treated SBP powder was added, and the mixture was homogenized at 80°C and 900 rpm for 30 min. The resulting viscous dopes were cast into 145 x 21 mm Petri dishes, allowed to degas, and thermally cured in a convection oven at 60°C for 36 h to yield the finalized SBP-based vegan leather (Fig. 1). Sample codes are designated by SBP content in grams (prefix SBP2/4/6), binder dominance (suffixes -SG for starch-dominant and -AG for alginate-dominant), and plasticizer type (-G for liquid glycerol, -So for solid sorbitol, and -SoG for their blend).

Characterization of produced SBP-based vegan leathers

- **Fourier transform infrared (FT-IR) spectroscopy.** The chemical structure of the SBP-based vegan leather was analyzed by ATR-FTIR (Perkin Elmer, Spectrum 100) in the range of 4000 to 650 cm^{-1} at a resolution of 4 cm^{-1} [17, 18].

- **Water vapor transmission rate (WVTR).** The WVTR of SBP-based vegan leathers was measured gravimetrically according to the ISO 14268 standard [19, 20]. Prior to testing, samples were dried at 105°C to a constant mass. Test tubes containing 15 g of anhydrous silica gel were then sealed with the vegan leather samples and secured with parafilm. The assembly weights were monitored at 24, 48, and 120 h over a five day period, and WVTR was calculated using Eqn. 1:

$$\text{WVTR} = \frac{\Delta W / \Delta t}{A} \quad (1)$$

where $\Delta W / \Delta t$ is the amount of water vapor gain per unit time (g/h) and A is the exposed area of the vegan leather (m^2).

- **Water solubility.** To evaluate moisture stability, the water solubility of vegan leathers was determined [21]. Samples (2x2 cm) were dried at 105°C for 1.5 h to a constant initial dry weight (W_0), then immersed in 40 mL of distilled water for 30 min. After filtering with Sartorius 391 filter paper and draining for 40 min, the specimens were dried at 105°C for 24 h to determine their final dry weight (W_t). The water solubility percentage (WS%) was calculated according to Eqn. 2:

$$\text{WS (\%)} = \frac{W_0 - W_t}{W_0} \times 100 \quad (2)$$

- **Thickness.** The thickness of the SBP-based vegan leathers was measured using a digital micrometer (0.1 mm precision). In accordance with the ISO 2589 standard, measurements were taken at three different points to determine the average value [22].

- **Mechanical characterization.** The mechanical properties of SBP-based vegan leathers were characterized using an Instron 5982 electromechanical universal testing machine at $22 \pm 0.5^\circ\text{C}$ with a crosshead speed of 100 mm/min, following the ISO 3376 standard [23–25]. Maximum tensile force, percentage elongation, and tensile modulus were recorded. The Young's modulus (E) was evaluated from the stress-strain curves according to Eqn. 3:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L_0} \quad (3)$$

where σ is the stress (MPa), ε is the strain, F is the force (N), A is the cross-sectional area (mm^2), ΔL is the extension (mm), and L_0 is the initial gauge length (mm).

RESULTS AND DISCUSSION:

FT-IR spectroscopy

FT-IR spectroscopy was employed to elucidate the functional groups and intermolecular interactions within the SBP-based vegan leathers (Fig. 2).

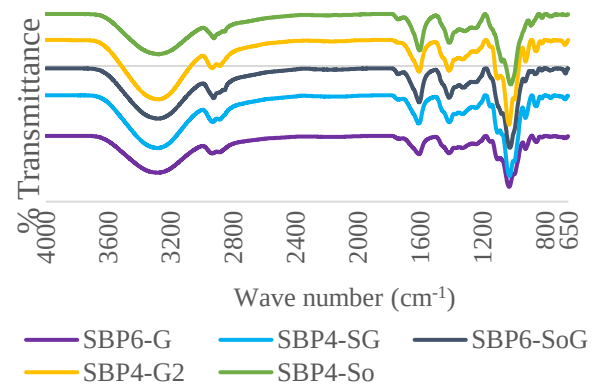


Figure 2. FT-IR spectra of SBP6-G, SBP4-SG, SBP6-SoG, SBP4-G2 and SBP4-So

The broad, intense bands at 3300–3500 cm^{-1} correspond to -OH stretching vibrations. Since SBP, starch, glycerol, and sorbitol are rich in hydroxyl moieties, peak intensities reflect moisture or plasticizer concentrations; for instance, the higher intensity in SBP6-SoG compared to SBP6-G indicates higher glycerol content [26]. The 2900–3000 cm^{-1} region represents aliphatic C-H stretching from SBP cellulose/hemicellulose, starch glucose units, and glycerol methylene ($-\text{CH}_2-$) groups, with intensity variations between SBP4-G2 and SBP4-So

directly correlating with glycerol concentration [27, 28]. The C=O stretching region ($1600\text{--}1700\text{ cm}^{-1}$) features carbonyl peaks from sodium alginate carboxylate ($-\text{COO}^-$) groups; where asymmetric stretching at $1600\text{--}1650\text{ cm}^{-1}$ and symmetric stretching near 1400 cm^{-1} confirm the alginate binder's presence [29]. The $1000\text{--}1200\text{ cm}^{-1}$ interval covers C-O stretching from carbohydrates (starch, SBP) and sorbitol, where peaks at $1050\text{--}1100\text{ cm}^{-1}$ match starch glycosidic linkages [30] and the peak around 1150 cm^{-1} stemming from SBP cellulose. Finally, sodium alginate displays a unique peak near $900\text{--}950\text{ cm}^{-1}$ related to its uronic acid units [31].

Barrier properties and hydrolytic stability

The water vapor transmission rate (WVTR) and water solubility (WS) of SBP-based vegan leathers are detailed in Fig. 3 and Table 2, showing significant dependence on SBP concentration, bio-material binder type, and plasticizer parameters.

Formulations with higher SBP content, such as SBP6-G (34.2%) and SBP6-SoG (35.7%), exhibited moderately increased permeability due to diffusion-facilitating micro-voids, yet achieved the lowest water solubility (31% for SBP6-G) [32]. This structural stability is attributed to the high cellulose and lignin content in SBP, which acts as a vapor hydrophobic reinforcement within the carbohydrate matrix to hinder water penetration. Exceptional barrier profiles were noted in SBP4-AG ($1\text{ g/m}^2\cdot 120\text{ h}$) and SBP2-SG ($3\text{ g/m}^2\cdot 120\text{ h}$). The balanced starch/sodium alginate network in SBP4-AG enhanced path tortuosity, restricting moisture transmission; however, sodium alginate-rich sets (AG series) inherently displayed higher dissolution tendencies up to 89% in the absence of additional cross-linking [28, 29].

Plasticizer type and dosage decisively influenced both moisture transport and matrix degradation. Glycerol-doped formulations (e.g., SBP4 series G1 to G3) exhibited higher WVTR and WS values because increasing glycerol content from 38.7% to 55.7% expanded the free volume and enhanced surface moisture solubility [33, 34].

Conversely, the sorbitol-plasticized SBP4-So sample demonstrated superior hydrolytic resistance and a more compact architecture; despite its low plasticizer ratio (27.3%), it maintained a balanced solubility of 47% and low permeability through a tortuous path created by sorbitol's higher crystallinity. Benchmarked against traditional shoe-upper leather, which exhibits high breathability ($4.6\text{ mg/cm}^2\cdot\text{h}$) due to a porous fibrillar structure, the engineered SBP vegan leathers present a barrier-centric profile [25].

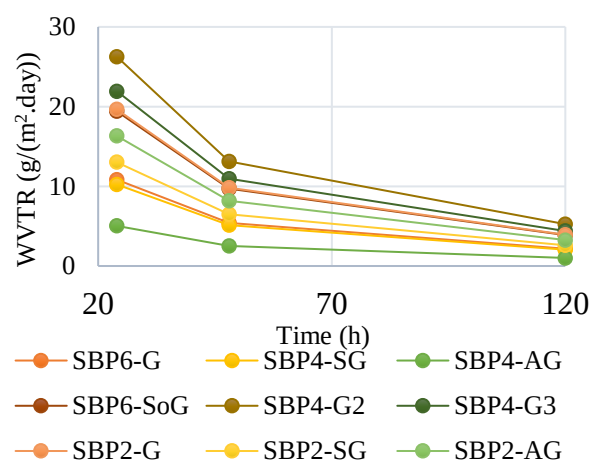


Figure 3. Time-dependent WVTR trends over a 120-h period

Table 2. Influence of SBP content and plasticizer characteristics on water solubility and WVTR of SBP-based vegan leathers

Sample	WS (%)	WVTR ($\text{g/m}^2\cdot\text{day}$)	Plasticizer type
SBP6-G	31	10.83	Glycerol
SBP6-SoG	45	13.02	Glycerol + sorbitol
SBP4-So	47	10.23	Sorbitol
SBP4-G1	41	19.41	Glycerol
SBP4-G2	37	5.03	Glycerol
SBP4-G3	51	16.32	Glycerol
SBP4-SG	45	26.26	Glycerol (starch-rich)
SBP4-AG	58	21.93	Glycerol (alginate-rich)
SBP2-G	56	19.65	Glycerol
SBP2-SG	77	5.03	Glycerol (starch-rich)
SBP2-AG	89	-	Glycerol (alginate-rich)

Their daily WVTR values (15–50 g/m²·day) closely align with dense, polymeric-coated commercial alternatives like Appleskin (0.4 mg/cm²·h), Desserto (0.5 mg/cm²·h), and Vegea (0.7 mg/cm²·h), staying highly competitive with traditional PU/PVC synthetics. While bio-based alternatives frequently encounter moisture-sensitivity challenges, the optimized stability of SBP6-G (31% WS) and SBP4-G2 (37% WS) demonstrates that adjusting binder-filler and plasticizer configurations successfully regulates water resistance. As emphasized by Haneef *et al.* [35], plant-based composites offer superior functional comfort through regulated moisture transfer compared to purely synthetic materials, validating these durable SBP formulations for advanced footwear and upholstery applications.

Mechanical characterization and tensile performance

The mechanical properties of SBP-based vegan leathers were systematically evaluated to elucidate the effects of filler-binder interactions and plasticizer types (Table 3).

Table 3. Thickness (mm), tensile strength (MPa), elongation (%) and Young modulus (MPa) of produced SBP-based vegan leathers

Sample	Thickness (mm)	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (MPa)
SBP6-G	1.2	6.00	53.81	7.19
SBP4-SG	0.7	4.49	15.40	66.58
SBP6-SoG	1.1	5.95	23.43	29.29
SBP4-G2	0.8	3.32	41.89	6.38
SBP4-So	0.5	22.26	2.34	1374.22

The mechanical profile is predominantly governed by SBP loading and the molecular characteristics of the plasticizing agent. Formulations with elevated SBP content, such as SBP6-G and SBP6-SoG, exhibited moderate tensile strength. While SBP fibers function as structural reinforcement, an excessive filler to binder ratio disrupts the polymer matrix's continuity, promoting stress concentration points and limiting tensile strength relative to optimized intermediate formulations [36].

Fig. 4 illustrates the macrostructural appearance and flexibility of the fabricated vegan leathers. A profound divergence in mechanical performance is observed based on the specific plasticizer utilized.



Figure 4. Macrostructural appearance of the fabricated A) SBP4-SG and B) SBP6-SoG

Glycerol-plasticized SBP4-G2 demonstrated a ductile profile with low rigidity, whereas SBP4-So outperformed all variations, achieving peak tensile strength of 22.26 MPa and Young's modulus of 1374.22 MPa. This substantial enhancement is linked to the higher crystallinity and distinct molecular configuration of sorbitol. While smaller polyols like glycerol increase free volume and chain mobility, sorbitol's larger structure and higher hydroxyl density facilitate a denser hydrogen-bonded network, resulting in a more compact and rigid architecture [37]. In alignment with polymer theory, an inverse correlation was recorded between elongation at break and Young's modulus (Fig. 5). Formulations with high glycerol content (e.g., SBP4-SG and SBP4-G2) exhibited superior ductility due to reduced intermolecular forces and enhanced chain slippage ("lubrication effect") [38]. Conversely, SBP4-So transitioned toward a high-strength, semi-brittle state. These findings confirm that the mechanical profile can be tailored for diverse industrial needs by strategically selecting the plasticizer and SBP loading.

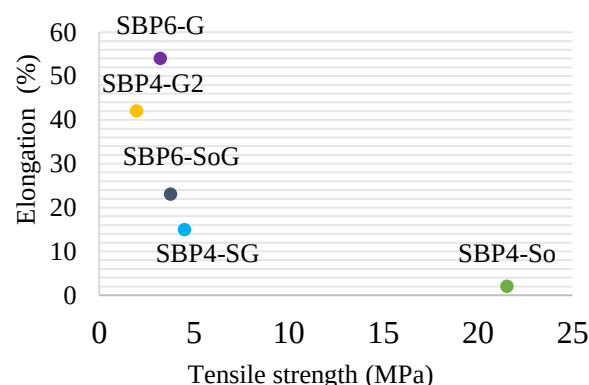


Figure 5. Relationship between tensile strength and elongation at break of SBP-based vegan leathers

The technical performance of SBP4-So exhibits highly competitive characteristics when benchmarked against commercial leather and contemporary alternatives reported by Meyer *et al.* [39]. The thickness of the synthesized specimens (0.5–1.2 mm) directly aligns with commercial bio-based alternatives like Appleskin (1.14 mm), Desserto (0.88 mm), and Vegea (1.06 mm). In terms of mechanical strength, traditional shoe leather

maintains the highest value at 39.5 N/mm²; however, alternatives like Appleskin (14.0 N/mm²), Vegea (9.4 N/mm²), and Muskin (0.2 N/mm²) fall substantially below the value achieved in this study. Notably, the tensile strength of SBP4-So successfully meets the industrial requirement for shoe uppers (>15 N/mm²). While Desserto (20.8 N/mm²) and SnapPap (24.9 N/mm²) present similar profiles, the superior load-bearing capacity of sorbitol-based SBP vegan leathers positions them as technically viable, sustainable candidates for high-durability applications.

CONCLUSION

This study demonstrates the potential of SBP as a sustainable reinforcing agent in starch and sodium alginate-based vegan leathers. FT-IR analysis confirmed robust hydrogen bonding interactions between the bio-material binders and lignocellulosic SBP fibers, proving it acts as an effective reinforcing filler. The thickness of the synthesized specimens directly aligns with commercial standards, while water solubility analyses revealed that the cellulosic nature of SBP combined with the crystalline structure of sorbitol enhanced hydrolytic resistance. Plasticizer type and filler ratio were critical to mechanical performance; the sorbitol-plasticized SBP4-So formulation exhibited the most outstanding profile, with tensile strength and Young's Modulus values that exceed the industrial limit for shoe-upper production and surpass commercial competitors. Regarding barrier properties, SBP4-AG and SBP2-SG displayed exceptional character with low transmission rates. While differing from the high breathability of traditional leather, these WVTR values align closely with commercial alternatives. In conclusion, the optimized SBP-based vegan leathers integrate low environmental impact with high mechanical strength, offering a technically viable and sustainable alternative to traditional synthetic PU/PVC materials in the textile, footwear, and upholstery sectors.

REFERENCES

1. C. R. China, M. M. Maguta, S. S. Nyandoro, A. Hilonga, S. V. Kanth, K. N. Njau, *Chemosphere*, **254**, 126847 (2020).
2. A. Kaya, B. Demir, C. Yilmaz, *J. Clean. Prod.*, **215**, 123 (2023).
3. K. Niinimäki, *Sustainable fashion in a circular economy*, Routledge, London, 2017, p. 1.
4. X. Liu, X. Zhang, X. Wang, O. Yue, H. Jiang, *Trends Biotechnol.*, **43**, 1104 (2025).
5. G. Venturelli, L. Guida, M. G. T. Fasani, S. Mantero, P. Petrini, M. Levi, *Appl. Mater. Today*, **44**, 102776 (2025).
6. J. Crouse, S. Sellers, K. Wawrousek, R. M. Sabino, *ACS Omega*, **10**, 12002 (2025).
7. Ethicwater, *Comprehensive guide on single-use plastics*, Ethicwater Reports, London, 2024, p. 1.
8. S. Golomeova Longurova, S. Risteski, S. Zhezhova, S. Jordeva, V. Dimitrijeva-Kuzmanoska, *Koža Obuća*, **74**, 7 (2025).
9. Bolt Threads, *What is Mylo™*, Technical Brief, Emeryville, 2024, p. 1.
10. Desserto, *Sustainable cactus-based biomaterial*, Product Whitepaper, Guadalajara, 2024, p. 1.
11. C. R. M. Sanchez, J. A. Torres, L. M. Gomez, *J. Nat. Fibers*, **18**, 641 (2021).
12. S. S. Muthu, M. Ramchandani, *Vegan alternatives for leather*, Springer, Singapore, 2024, p. 1.
13. TÜİK, *Turkish sugar industry waste statistics*, Turkish Statistical Institute, Ankara, 2023, p. 1.
14. J. F. Thibault, *Food Hydrocolloids*, **15**, 1 (2001).
15. B. Gökdemir, K. Sever, M. Atagür, İ. Şen, *J. Eng. Sci. Des.*, **13**, 791 (2025).
16. M. K. ResearchGate, *Ferulic acid crosslinking in pectin networks*, *Polym. Briefs*, **4**, 15 (2019).
17. H. N. Phan, S. Okubayashi, *Cellulose*, **32**, 4939 (2025).
18. P. Narayanan, S. K. Janardhanan, *Collagen Leather*, **6**, 1 (2024).
19. B. W. J. Ko, S. H. Park, Y. J. Kim, *Polym. Test.*, **76**, 101 (2019).
20. ISO 14268, *Leather-Physical and mechanical tests-Determination of water vapour permeability*, International Organization for Standardization, Geneva, 2023, p. 1.
21. S. Farris, L. Piergiovanni, J. M. Krochta, *Food Hydrocolloids*, **30**, 383 (2013).
22. ISO 2589, *Leather-Physical and mechanical tests-Determination of thickness*, International Organization for Standardization, Geneva, 2016, p. 1.
23. ASTM D882-18, *Standard test method for tensile properties of thin plastic sheeting*, ASTM International, West Conshohocken, 2018, p. 1.
24. ISO 527-3, *Plastics—Determination of tensile properties—Part 3*, International Organization for Standardization, Geneva, 2018, p. 1.
25. ISO 3376, *Leather-Physical and mechanical tests-Determination of tensile strength and percentage elongation*, International Organization for Standardization, Geneva, 2020, p. 1.
26. M. Kacuráková, R. H. Wilson, *J. Appl. Polym. Sci.*, **82**, 1 (2001).
27. R. M. Silverstein, *Spectrometric identification of organic compounds*, Wiley, New York, 2014, p. 1.
28. L. Pereira, A. M. Silva, G. T. Sousa, *Carbohydr. Polym.*, **93**, 402 (2013).
29. G. T. Grant, E. R. Morris, D. A. Rees, *Nature*, **215**, 756 (1967).
30. K. Bledzki, A. Jaszkievicz, *Compos. Sci. Technol.*, **70**, 1687 (2010).

31. H. H. Tønnesen, J. Karlsen, *Drug Dev. Ind. Pharm.*, **28**, 621 (2002).
32. D. Gorecka, M. Krzywdzinska, A. Szwengiel, *Carbohydr. Polym.*, **291**, 119502 (2022).
33. S. Chen, B. Zhang, J. Wang, *Polym. Test.*, **89**, 106621 (2020).
34. Syarifuddin, N. Haliza, N. Izzah, M. M. Tahir, A. Dirpan, *Foods*, **14**, 1219 (2025).
35. M. Haneef, H. Bertrand, D. S. Cloutier, *Sci. Rep.*, **7**, 46647 (2017).
36. C. Yılmaz, B. Sever, A. E. Öztürk, *Waste Biomass Valorization*, **13**, 1123 (2022).
37. S. Demir, M. Atagür, İ. Şen, *Sustain. Mater. Technol.*, **35**, 105678 (2023).
38. E. Öztürk, K. Sever, B. Gökdemir, *J. Clean. Prod.*, **312**, 127689 (2021).
39. M. Meyer, S. Dietrich, H. Schulz, A. Mondschein, *Coatings*, **11**, 226 (2021).