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REVIEW

Grape Waste as Leather-Like Material Alternative: A Comprehensive Review of Ancient Practices, Current Technologies, and Future Trends

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ABSTRACT: Grape by-product of the wine industry, rich in polyphenols, tannins, lignin, and natural waxes, the chemical constituents grape skins 45%–55%, seeds 25%–35%, and stems or stalks 25%–35% weight of grape provide intrinsic cross-linking, mechanical reinforcement, antioxidant activity, and water resistance, closely replicating the effects of conventional vegetable tanning without using toxic chemicals. This review comprehensively examines current eco-friendly extraction methods to isolate bioactive compounds, as well as fiber modification techniques to improve polymer compatibility. Composite fabrication involves blending processed grape waste fibers with bio-based polymers and renewable plasticizers to produce materials exhibiting competitive tensile strength, elasticity, and appealing surface aesthetics. Despite these advances, challenges such as limited mechanical durability, moisture sensitivity, cost constraints, and raw material supply scalability remain barriers to widespread adoption. Hybrid bio-leather strategies that combine grape waste with other natural fibers and biodegradable polymers show promise in enhancing performance while maintaining environmental benefits. Furthermore, emerging innovations in biotechnology, nanotechnology, and green chemistry are expected to drive improvements in material properties and production efficiency. Overall, grapes' leather-like materials transform winery by-products into high-value, eco-friendly materials suitable for applications in fashion, footwear, and upholstery. Continued research and industrial scale-up are critical to unlocking their full potential in expanding the sustainable materials market.

KEYWORDS: Grape waste; bio-based leather; leather alternatives; sustainable materials; hybrid bio-composites

1 Introduction

The global leather industry is one of the most important sectors in the fashion, footwear, automotive, and upholstery markets, with annual production exceeding 23 billion square feet of leather products [1,2]. Despite its economic significance, the conventional leather production chain remains highly resource-intensive and environmentally polluting. In response to ethical and environmental concerns, synthetic leather products have been developed as alternatives to animal-derived leather [3,4]. However, synthetic leather also has severe environmental impacts it is petroleum based; Polyvinyl Chloride (PVC) and Polyurethane (PU) are non-biodegradable and contribute to long-term micro-plastic pollution [5,6]. Furthermore, their production and disposal release volatile organic compounds (VOCs), including phthalates and dioxins, which are harmful to human health and ecosystems [6]. These combined issues showed the crucial need for bio-based, biodegradable leather-like material alternatives that meet the objective of reducing environmental impacts.

Grape pomace-based composites show moderate strength (3–5 MPa) and stiffness (200 MPa), lower than bovine (8–25 MPa) and PU leathers (10–25 MPa), with limited flexibility (15%–25% elongation). Their hydrophilic components reduce barrier performance, but reinforcement with biopolymers or PU coatings improves stability while retaining environmental benefits [7,8].

One inspiring approach is bio-based, bio-degradable leather-like material alternatives, which is grape pomace, a major by-product of winemaking. Global wine production reached 258 million hectoliters in 2023, resulting in more than 14 million tonnes of grape marc being generated annually [6,9,10]. Grape waste, which includes skins, seeds, and stems, accounts for 20%–30% of the weight of processed grapes [9]. Much of this biomass is discarded through composting, landfilling, or incineration, contributing to methane emissions, leachate formation, and the leaching of residual phenolic compounds into the environment [11]. Consequently, sustainable up-cycling of grape waste presents significant advantages by alleviating agro-industrial waste accumulation, reducing associated greenhouse gas (GHG) emissions, and replacing resource-intensive animal and synthetic leathers with bio-based alternatives. Grape pomace is chemically rich in cellulose, hemicellulose, lignin, polyphenols, waxes, and tannins, making it an ideal candidate for biopolymer development [12]. Its lignocellulose matrix provides structural reinforcement, while tannins can act as natural cross-linkers and impart natural coloration. These features enable grape waste-derived materials to contribute to the mechanical strength and aesthetic qualities of conventional leather. Grape waste-based leathers, made from wine by-products such as lignocellulosic residues, polyphenols, and oils, offer tensile strengths of 3–10 MPa and elongations of 15%–25%, similar to the lower range of natural leather. However, their strength (3–5 MPa) and stiffness (200 MPa) remain lower than those of natural (bovine) (8–25 MPa) and PU leathers (10–25 MPa), and their hydrophilic nature limits water resistance. Reinforcing these composites with biopolymers or applying PU coatings can significantly improve mechanical stability and barrier properties while maintaining their eco-friendly advantages Table 1 below [13].

Table 1: Mechanical and barrier properties of grape waste–based, conventional, and synthetic leathers

Material type	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (MPa)	Tear strength (N mm^{-1})	Water Absorption/WVTR	References
Grape waste–based bio-leather (lab-scale composite)	3.5–5.0	15–25	180–220	3–5	High (10%–15% water uptake); WVTR ≈ 1500–2200 g m^{-2} day^{-1}	[8,14]
Commercial grape-based "Vegea®" leather	Equivalent to ≈ 7–10 MPa (>350 N/5 cm)	<30	—	>20 N	Low water uptake; WVTR ≈ 500–800 g m^{-2} day^{-1}	[15]
Natural bovine leather (upper grade)	8–25	40–70	60–90	20–30	Moderate (8%–12%); WVTR ≈ 800–1500 g m^{-2} day^{-1}	[16]
Synthetic PU leather (microporous type)	10–25	100–300	20–60	25–35	Very low (<5%); WVTR ≈ 200–600 g m^{-2} day^{-1}	[17,18]

Compared to other bio-leathers, such as mycelium (2–12 MPa, 20%–80%), pineapple-leaf fiber (12–25 MPa, 10%–20%), and bacterial-cellulose (3–20 MPa), grape waste materials show intermediate mechanical performance, stronger than unreinforced cellulose but less robust than fiber- or polymer reinforced alternatives. Their main advantage lies in sustainability, transforming abundant agro-waste into leather-like materials with similar aesthetics, though further improvements in crosslinking, reinforcement, and coatings are needed to enhance durability and flexibility Table 2 below [19].

Table 2: Comparative properties of grape waste compared with other bio-based leather alternatives

Material type	Principal source & matrix	Tensile strength (MPa)	Elongation at break (%)	Distinct advantages	Limitations	References
Grape waste–based leather	Grape pomace (skins, seeds) blended with PU, PHA, or, cellulose matrix	3–10	15–25	Valorizes wine waste; aesthetic resemblance to leather	Moderate strength; moisture sensitivity	[20,21]
Fungal (mycelium) leather	Mycelial mats of *Ganoderma*, *Pleurotus*, etc.	2–12	20–80	Renewable, tunable porosity, biodegradability	Sensitive to moisture; mechanical variation	[22]
Pineapple-leaf fiber (Piñatex®)	*Ananas comosus* fibers with PLA/PU binder	12–25	10–20	High tensile strength; durable	Stiff; limited drape	[23–25]
Kombucha (bacterial cellulose) leather	Bacterial cellulose from *Komagataeibacter* spp.	3–20	2–40	Biocompatible; smooth texture	Brittle; high water uptake	[19]
Conventional bovine leather	Collagen fiber network (animal hide)	8–25	40–70	Strong, flexible, breathable	HiGH environmental footprint	[15]

Startups such as Vegea in Italy have already demonstrated proof of concept by producing flexible, durable, and attractive grape-based leather substitutes for applications in fashion, accessories, and interior design [26,27]. However, according to researchers [16,20,28], there is a gap in the available data on long-term durability, mechanical properties, water resistance, biodegradability, and chemical safety. These limitations currently hinder the use of grape waste-based materials in demanding product categories such as footwear and outdoor goods, where high water resistance and mechanical strength are essential.

To overcome these limitations, recent studies have focused on hybridization strategies that integrate grape pomace fibers with complementary bio-based constituents. Hybrid bio-leather composites are typically developed by blending grape waste with reinforcing natural fibers (hemp, banana), biodegradable polymers (polyhydroxyalkanoates, polylactic acid), and eco-friendly cross-linkers (tannic acid, enzymatic agents), which collectively improve tensile strength, flexibility, hydrophobicity, and processing performance [29]. Hybridization with bio-based polymers, nano-cellulose, or lignocellulosic fibers from other agricultural residues represents a promising strategy to address these gaps. Generally, this review provides a comprehensive inspection of grape waste as sustainable leather like material alternative. It begins by contextualizing the historical uses of grapes and their by-products in artisanal material production, followed by an analysis of the chemical and structural properties of grape waste relevant to biopolymer engineering. Finally, it identifies the knowledge gaps, technical challenges, and future research priorities required to advance grape waste derived leather like material alternatives for the global fashion, footwear, and leather goods industries within a circular bio economy basis.

2 Traditional and Historical Uses of Grape Waste

The historical use of grape by-products extends far beyond winemaking, reflecting a deep-rooted understanding of resource circularity in pre-industrial societies. Archeological evidence indicated that ancient Mediterranean civilizations including the Egyptians, Greeks, and Romans developed diverse applications for grape pomace, often referred to as vinaccia or marc [30]. While direct use in leather tanning is sparsely documented, historical records suggest the use of grape based extracts as natural mordents, antioxidants, and tanning adjuncts in various organic materials, including hides and textiles [31,32]. The polyphenolic richness of grape skins and seeds, particularly tannins and anthocyanins, may have contributed to their use in rudimentary vegetable tanning practices in early agrarian communities. In early Islamic and Byzantine textile workshops, grape-based residues were reportedly mixed with other plant materials such as oak bark or sumac for fabric dyeing and hide curing, suggesting an empirical understanding of their preservative and stabilizing properties [33,34]. Similarly, in medieval Iberian and Persian contexts, winemaking residues were sometimes incorporated into organic dye baths, where their pigmentation and astringent properties aided in fixing dyes to natural fibers and softening animal skins [35]. Historical records from Mediterranean and Near Eastern civilizations showed the use of grape derivatives, particularly tannin-rich grape skins and seeds, in early leather tanning practices. Tannins, polyphenolic compounds abundant in grape pomace, were traditionally employed as natural tanning agents due to their ability to stabilize collagen fibers and impart water resistance [36]. In Ancient Egypt, Greece, and Rome, grape marc was reportedly combined with other plant extracts such as oak bark and sumac to produce durable leathers for clothing, footwear, and armor [37].

3 Chemical Composition and Structural Characteristics of Grape Waste

Grape waste, the primary solid by-product of winemaking, comprises approximately 45%–55% grape skins [38], 25%–35% seeds, and 25%–35% stems or stalks by weight (Fig. 1) [39,40]. This lignocellulosic matrix is rich in biopolymers and bioactive compounds that make it a promising raw material for sustainable leather-like material alternatives. The structural framework of grape pomace is largely formed by cellulose, hemicellulose, and lignin, which provide mechanical resilience and biodegradability [41,42]. Grape skins are particularly rich in polyphenols, including anthocyanins, flavanols, tannins, and hydroxycinnamic acids. These compounds exhibit antioxidant, antimicrobial, and cross-linking properties essential in natural tanning and collagen stabilization [43,44]. Skins also contain natural waxes and pectins, which enhance the hydrophobicity and flexibility of derived materials [45]. Grape seeds contribute significantly through their lipid content, primarily unsaturated fatty acids, which improve water resistance, and pro-anthocyanins (condensed tannins), which strengthen binding and durability in composites. These tannins form stable cross-links with collagen fibers, mimicking the principle used in vegetable tanning [46–49]. Stems or stalks, while lower in phenolics, are rich in cellulose, hemicellulose, and lignin. Their high lignin content provides rigidity and structural support but may necessitate chemical or enzymatic pretreatments to enhance compatibility with polymer matrices [9]. The detailed chemical composition of the individual grape waste fractions, including polyphenols, tannins, lignocellulosic components, lipids, proteins, and mineral content, is summarized in (Table 3).

Collectively, the combination of polyphenols, lipids, biopolymers, and waxes gives grape pomace intrinsic properties ideal for bio-based leather development, biodegradability, mechanical strength, antimicrobial activity, hydrophobicity, and natural coloration. A clear understanding of the composition and structural organization of these components is needed to optimize extraction, processing, and cross-linking methods for high-performance, sustainable leather substitutes.

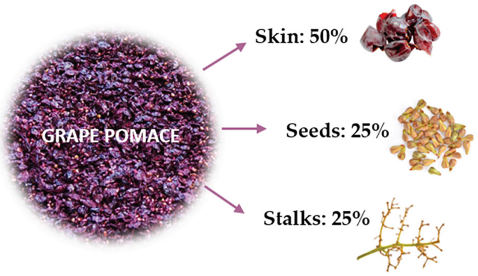

Figure 1: Solid compositions of grape pomace. [Adapted with Permission from Ref. [38]. Copyright © 2025, MDPI Ltd.]

Table 3: Chemical composition of grape waste fractions (% Dry weight basis)

Chemical component	Grape skins (%)	Grape seeds (%)	Grape stalks (%)	Description	References
Moisture	55–65	45–60	50–70	Varies with processing and cultivar	[50]
Total polyphenols	5.0–10.5	12.0–18.0	3.0–7.0	Natural tanning agents and antioxidants	[51,52]
Tannins	2.5–6.0	7.5–15.0	1.0–4.0	Crosslink collagen, key for tanning	[53]
Cellulose	15.0–25.0	10.0–15.0	30.0–45.0	Structural fiber; mechanical reinforcement	[54]
Hemicellulose	15.0–22.0	8.0–12.0	25.0–35.0	Fiber matrix component	[55]
Lignin	5.0–10.0	8.0–14.0	20.0–30.0	Provides rigidity; affects biodegradability	[56]
Waxes & Lipids	3.0–5.0	10.0–20.0	1.0–3.0	Surface properties: water resistance	[57]
Proteins	1.0–3.0	5.0–7.0	1.0–2.0	Minor; may influence cross-linking	[58]
Ash (Minerals)	1.5–3.5	1.0–2.5	4.0–6.0	Residual mineral content	[59]

4 Fabrication of Grape Waste Leather-Like Material Alternative

4.1 Extraction of Bioactive Components

Quantitative characterization of these fractions reveals considerable variability depending on grape variety, region, and extraction conditions. Typically, seeds account for 38%–52% of total pomace dry weight, skins for 28%–40%, and stems for 10%–15%. The overall extraction yield from grape pomace using conventional solvent methods ranges from 20%–35% (w/w), while advanced green techniques such as ultrasound- or supercritical CO_2-assisted extraction can achieve yields up to 45%–55%. Chemically, grape seeds are rich in lipid (oil) content ranging from 10%–20%, primarily composed of linoleic (65%–75%) and oleic (15%–20%) fatty acids, while skins contain lower oil levels (<5%) but significantly higher polyphenolic compounds (25–55 mg Gallic acid equivalents (GAE)/g dry weight) [60]. The total phenolic content of whole pomace typically falls within 20–40 mg GAE/g, though ethanol–water extraction may yield up to 60 mg GAE/g in red grape varieties. Tannins (8%–12%) and cellulose/hemicellulose (25%–35%) in the skin fraction contribute to the structural and crosslinking potential of grape waste in bio-composite matrices. Such compositional richness, combining phenolic antioxidants, unsaturated lipids, and polysaccharides, enables the formation of flexible, naturally colored, and partially hydrophobic films. Compared to other agro-residues (e.g., pineapple leaves or rice husks), grape pomace exhibits higher polyphenol density and moderate lipid content, offering both reactive sites for crosslinking and internal plasticization potential in bio-leather formulations (Table 4) below [61].

Table 4: Composition and extraction yields of grape waste

Grape waste fraction	Extraction yield (%)	Oil content (%)	Total polyphenols (mg GAE/g drywt)	Major components	Function	References
Seeds	20–25 (solvent)/up to 45 ($SC\text{-}CO_2$)	10–20	5–15	Linoleic & oleic acids, proanthocyanidins	High antioxidant oil fraction	[61,62]
Skins	10–15	<5	25–55	Anthocyanins, tannins, cellulose	High pigment & polyphenol content	[61,62]
Stems	5–10	<3	10–25	Lignin, tannins, fiber	Useful for reinforcement	[21]
Whole pomace (mixed)	20–35	6–12	20–40	Polyphenols, cellulose, residual sugars	Balanced composition for composites	[21,61,62]
Pomace (green extraction)	40–55 (ultrasound/ $SC\text{-}CO_2$)	12–18	Up to 60	Concentrated phenolics & oil	High recovery efficiency	[63,64]

Grape pomace, the primary solid by-product of winemaking, composed of grape skins, seeds, and stalks, first undergoes a drying process to lower its natural moisture content. This step is essential to inhibit microbial growth, extend shelf life, and enhance subsequent processing [9,65]. Drying is typically carried out under controlled thermal or convective conditions to preserve thermosensitive phytochemicals. Once dried, mechanical fractionation techniques such as sieving or density-based separation are applied to isolate the individual anatomical components of the pomace. This separation enables the targeted use of each fraction's biochemical constituents, improving both extraction efficiency and the performance of final products [49,66].

Subsequently, green extraction technologies are employed to recover high-value bioactive compounds from each fraction. The extraction of valuable compounds from grape waste has been achieved through several conventional and emerging techniques, each with distinct advantages and limitations summarized in (Table 5). Conventional solvent extraction (using ethanol, methanol, or acetone mixtures) remains the most accessible and cost-effective approach, offering moderate yields (20%–35%) and broad compound recovery [67]. However, it typically involves toxic or volatile solvents, high solvent consumption, and extended processing times, which limit industrial scalability and environmental compliance. Supercritical CO_2 extraction (SC-CO_2) provides a cleaner and tunable method for obtaining high-purity seed oils (yield up to 45%) and lipophilic antioxidants, with the advantages of solvent-free recovery, shorter extraction times, and thermal protection of bio-actives. Its major drawback is the high equipment cost and the need for specialized pressure systems, which restrict its use to high-value applications [68]. Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) have emerged as green alternatives, enabling enhanced mass transfer, reduced solvent usage (by 30%–50%), and higher polyphenol yields (up to 60 mg GAE/g) compared to conventional methods. Nevertheless, both methods can suffer from local overheating, uneven extraction, and challenges in continuous-scale operation [69].

Enzyme-assisted extraction (EAE), which utilizes celluloses and pectinases to degrade grape cell walls, offers improved recovery of bound polyphenols and tannins, but its efficiency depends strongly on enzyme specificity, cost, and pH sensitivity [70]. Ultrasound-assisted extraction (UAE) and supercritical carbon dioxide (SC-CO_2) extraction are particularly favored for their environmentally friendly profiles and selectivity in extracting polyphenols and condensed tannins. These phenolic compounds exhibit potent antioxidant activity and strong protein cross-linking ability, making them valuable as functional tanning agents in bio-based leather matrices [52,71,72]. In parallel, grape seed oil is obtained through cold pressing or solvent extraction. Rich in unsaturated fatty acids, especially linoleic acid, the oil acts as a natural plasticizer and hydrophobic agent in composite formulations [73,74]. The remaining lignocellulosic fraction containing cellulose, hemicellulose, and lignin serves as the structural reinforcement phase in bio-based leather composites. These biopolymers provide mechanical strength, dimensional stability, and biodegradability to the end product.

To improve polymer-matrix compatibility and interfacial bonding, pretreatments such as alkaline treatment, enzymatic processing, or steam explosion may be necessary [9,75]. This holistic bio-refinery approach optimizes resource utilization and binds the full chemical and structural potential of grape pomace to create high-performance, sustainable leather alternatives.

Table 5: Summary of common extraction methods for grape waste components

Extraction method	Typical yield/Content	Strengths	Weaknesses	Overall suitability	References
Conventional solvent extraction	20%–35% total extract; polyphenols ≈ 30–40 mg GAE/g	Simple, low-cost, widely applicable	High solvent use, toxicity, and long-term	Economically feasible for large-scale	[67]
Supercritical CO_2 extraction (SC-CO_2)	Seed oil up to 45%; high-purity phenolics	Solvent-free, tunable, high-quality extract	High equipment and energy costs	Best for high-value compounds	[68]
Ultrasound-Assisted Extraction (UAE)	Polyphenols up to 60 mg GAE/g	Fast, energy-efficient, and less solvent	Uneven heating, scale-up issues	Promising for green extraction	[76]

(Continued)

Table 5 (continued)

Extraction method	Typical yield/Content	Strengths	Weaknesses	Overall suitability	References
Microwave-Assisted Extraction (MAE)	Yield ↑ 25%–40% vs. solvent methods	Rapid, reduced solvent/time	Local overheating, limited scale-up	Effective for lab/pilot scale	[69,76]
Enzyme-Assisted Extraction (EAE)	10%–30% higher phenolic recovery	Mild conditions, high selectivity	High enzyme cost, pH sensitivity	Sustainable for targeted bioactives	[70]

4.2 Milling, Processing, and Modification of Grape Biomass

The separated grape pomace fractions are first subjected to size reduction through milling into fine powders or microfibers (<100 μm), a critical step to ensure uniform dispersion within polymer matrices and enhance composite performance [77,78]. To improve interfacial adhesion between the lignocellulosic fibers and the polymeric phase, surface modification techniques such as enzymatic and alkaline treatments are employed. Enzymatic hydrolysis using cellulose and pectinases selectively targets amorphous regions, increasing surface roughness and exposing reactive hydroxyl and carboxyl functional groups, while mild alkaline treatments (NaOH) remove hemicellulose and waxes, increase porosity, and strengthen chemical and physical interactions with the polymer matrix [79].

Polyphenolic extracts derived from grape skins and seeds can then be reintroduced into the lignocellulosic fraction to further enhance cross-link density. This step significantly improves tensile strength, thermal stability, and enzymatic resistance of the resulting composite [80,81]. The inherent molecular composition of grape pomace rich in condensed tannins, anthocyanins, phenolic acids, lignocellulosic fibers, pectins, and natural waxes provides intrinsic cross-linking capability and material stabilization potential [48,82]. Condensed tannins and hydrolysable polyphenols, particularly abundant in grape seeds (up to 15%–20% dry weight) and skins, possess multiple hydroxyl substituents and aromatic rings that enable strong interactions with the amino and carboxyl groups of collagen peptides. In bio-based leather-like materials, tannins and polyphenols act as natural crosslinking and stabilizing agents by forming hydrogen bonds and covalent interactions with polysaccharides, lignin, or protein-based binders. These interactions enhance mechanical integrity, water resistance, and oxidative stability, mimicking the effects of vegetable tanning in a collagen-free matrix [82,83]. These interactions stabilize the collagen triple-helix structure, reduce hydrophobicity, and enhance both thermal and proteolytic resistance. This mechanism closely parallels vegetable tanning with oak or sumac tannins but avoids the environmental hazards associated with chromium salts [48,84]. As a result, tannin-rich fractions of grape pomace not only improve the durability, dimensional stability, and performance of bio-based leather similarities but also provide a renewable and circular alternative to conventional tanning chemistries.

4.3 Composite Fabrication

The processed grape pomace powders and fibers are compounded with bio-based polymeric binders such as polyvinyl alcohol (PVA), polylactic acid (PLA), starch-based blends, or waterborne polyurethane (PU) to form composite matrices with superior structural and functional properties [74,85]. Renewable plasticizers, including grape seed oil, glycerol, and other low-molecular-weight polyols, are incorporated to improve flexibility and reduce brittleness [86]. Homogenization under controlled shear and temperature ensures uniform dispersion of the grape biomass within the polymer matrix, strengthening fiber matrix interfacial interactions through hydrogen bonding, hydrophobic forces, π–π stacking, and covalent cross-linking mediated by polyphenolic constituents [74,87]. The overall processing pathway from grape pomace drying and fractionation to extraction, biomass modification, composite fabrication, and finishing is schematically illustrated in (Fig. 2) below.

The lignocellulosic fractions of grape skins and stalks, rich in cellulose, hemicellulose, and lignin, function as a fibrous reinforcement phase, imparting mechanical strength and dimensional stability. Polyphenolic compounds further enhance adhesion between the fibers and polymer chains through hydrogen bonding and aromatic π–π interactions, while simultaneously improving composite homogeneity [72,74]. Lipid-rich grape seed fractions complement this by contributing hydrophobicity, reducing water vapor permeability, and increasing durability [73]. Under handmade thermo-mechanical and enzymatic processing conditions, grape polyphenols can undergo auto-oxidation and oxidative polymerization, forming highly cross-linked, three-dimensional networks integrated with the lignocellulosic backbone [82,87]. These networks significantly improve tear resistance, mechanical integrity, and dimensional stability. Additionally, natural waxes and pectins inherent in grape pomace enhance surface smoothness, elasticity, and tactile quality, yielding leather-like materials with the mechanical performance, durability, and aesthetic properties necessary for high-performance leather similarities [88].

Compared with other lignocellulosic or fruit waste-based composites, grape waste-derived materials exhibit a distinctive combination of mechanical resilience and antioxidant functionality. Similar to pineapple leaf fiber (PALF), banana pseudostem, and coconut husk composites, grape pomace contains cellulose, hemicellulose, and lignin, which contribute to tensile strength and flexibility [20,70,89]. However, grape waste additionally provides natural polyphenols, tannins, and seed oils, which improve UV stability, antimicrobial activity, and color fastness, offering advantages in functional and aesthetic performance. While pineapple and banana fiber–based leathers demonstrate higher tensile strength (25–35 MPa) due to longer fiber morphology, grape waste composites typically reach 15–25 MPa, yet exhibit superior barrier and antioxidant properties. Compared to apple, mango, and citrus waste leathers, which require external cross-linkers or plasticizers, grape-based matrices can self-stabilize via phenolic–protein interactions, enhancing eco-sustainability and reducing chemical dependency. Overall, grape waste shows balanced mechanical and functional performance, positioning it as a versatile, bioactive, and circular alternative among plant- and fruit-based leather substitutes (Table 6) below [90,91].

Table 6: Comparison of grape waste–based composites with other lignocellulosic and fruit waste–based leather-like materials

Source material	Key components	Tensile strength (MPa)	Unique strength	Weakness	References
Grape pomace	Cellulose, lignin, polyphenols, oils	15–25	Antioxidant, UV-resistant, self-binding	Variable fiber length	[20,60]
Pineapple Leaf Fiber (Piñatex)	Cellulose, lignin	25–35	High strength, good flexibility	Requires plasticizer	[90,91]

(Continued)

Table 6 (continued)

Source material	Key components	Tensile strength (MPa)	Unique strength	Weakness	References
Banana Pseudo-stem Fiber	Cellulose, hemicellulose	20–30	Good strength, biodegradability	Low water resistance	[89]
Apple waste composite	Pectin, cellulose	10–20	Smooth surface, easy forming	Needs cross-linkers	[92]
Mango peel waste	Pectin, polyphenols	12–22	Biodegradable, glossy finish	Moderate mechanical strength	[93]

4.4 Shaping and Thermal Compaction

The homogenized composite slurry is subsequently processed into thin sheets using techniques such as solvent casting, extrusion, or compression molding, each of which enables precise control over thickness, microstructure, and fiber orientation [94]. Following initial sheet formation, hot-pressing is performed under controlled conditions typically at temperatures ranging from 80°C–120°C and pressures of 5–20 MPa to compact the material, densify the fiber–polymer matrix, and reduce residual porosity [87,95]. This thermomechanical step is critical for enhancing the dimensional stability of the composite and for improving its mechanical properties, as the elevated temperature and pressure facilitate further interfacial adhesion, polymer chain mobility, and fiber alignment within the matrix [82,96]. In addition, hot-pressing promotes secondary cross-linking reactions between polyphenolic constituents and polymer chains, resulting in an increased cross-link density that contributes to greater tensile strength, tear resistance, and overall durability in the final bio-based leather [97,98].

4.5 Surface Finishing

To replicate the texture, aesthetic qualities, and functional performance of conventional leather, the fabricated composite sheets undergo a sequence of finishing processes. Embossing or grain-patterning under controlled temperature and pressure is employed to recreate the characteristic surface morphology of natural leather while improving surface durability [96]. Bio-based coatings or wax emulsions derived from natural oils, plant resins, and polysaccharides are then applied to enhance water repellency, abrasion resistance, and tactile softness, while also acting as protective barriers against environmental degradation [98]. Natural dyeing using grape-derived anthocyanins or other plant-based pigments further imparts coloration without the need for synthetic dyes, reducing environmental impact [72]. The anthocyanin and polyphenolic compounds inherent in grape pomace additionally provide ultraviolet resistance and antioxidant stability in the final material [82,99] Together, these finishing treatments, combined with the preceding environmentally friendly extraction, biomass modification, and composite fabrication steps, fully exploit the chemical and structural potential of grape pomace. The resulting leather-like materials achieve the desired mechanical, aesthetic, and functional properties while being biodegradable, free from chromium and other harmful tanning agents, and aligned with circular economy principles. This integrated approach positions grape pomace–based composites as a sustainable alternative to traditional animal- and petroleum-derived leathers [84,100]

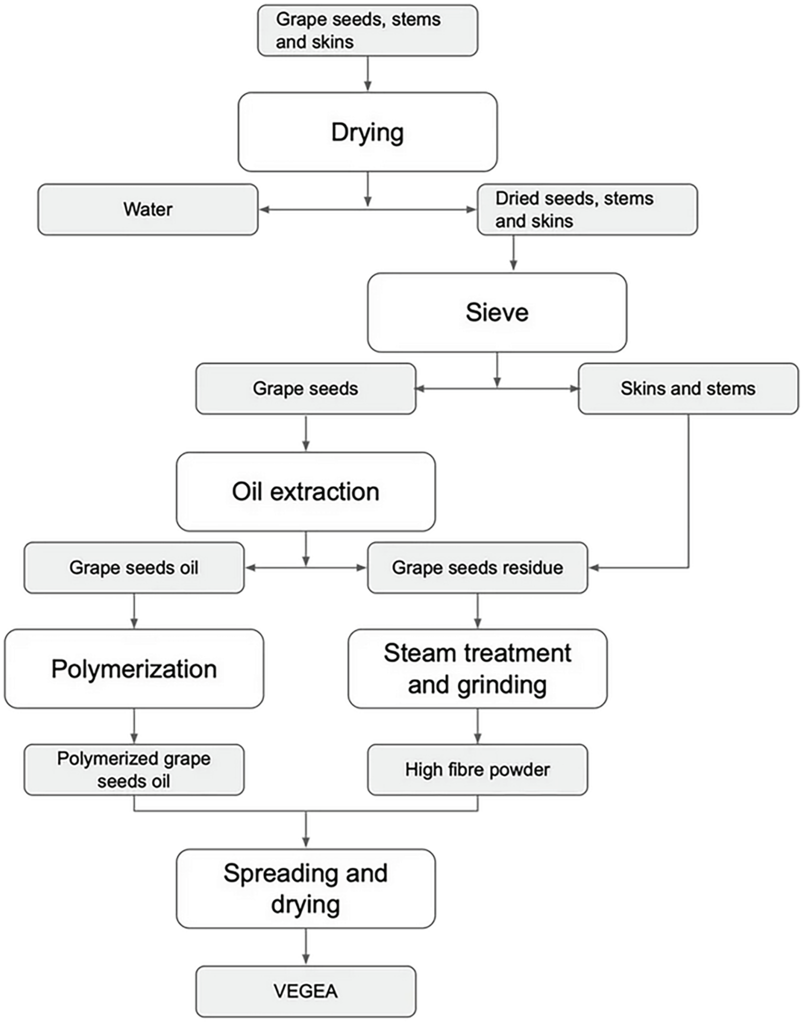

Figure 2: Fabrication of Grape waste alternative leather-like material. [Adapted with Permission from Ref. [101]. Copyright © 2020, VEGEA® Company Ltd.]

5 Physical, Mechanical, and Chemical Properties of the Grape Waste Alternative Leather-Like Material

5.1 Physical Properties

Grape leather-like material exhibits a density of approximately 0.8 to 1.2 g/cm^3, enabling lightweight, structurally sound materials suitable for diverse applications [74]. The thickness of grape leather can be tailored from 0.5 to 2.0 mm during fabrication, allowing control over flexibility and tactile properties [102]. Surface characteristics such as texture and natural pigmentation are achieved through embossing techniques and inherent anthocyanins from grape skins, providing an appearance comparable to traditional leather. Although grape leather is inherently hydrophilic due to cellulose content, its water resistance improves significantly with the incorporation of bio-based wax coatings derived from grape seed oil [103]. A comparative overview of key physical parameters of grape leather and other bio-based leather alter-natives is presented in (Table 7) below.

5.2 Mechanical Properties

Mechanically, grape leather demonstrates tensile strengths ranging between 8 and 25 MPa and Young's modulus values from 20 to 70 MPa, comparable to certain grades of animal leather and synthetic alternatives [104,105]. The elongation at break is typically between 20% and 60%, indicative of good elasticity and resistance to mechanical stress, which can be further enhanced by plasticizers such as grape seed oil [104,106]. Reinforcement with lignocellulosic fibers from grape pomace contributes to improved tear resistance and abrasion durability, especially when coupled with appropriate surface finishing [102].

5.3 Chemical Properties

Chemically, grape leather's matrix is enriched with polyphenolic compounds, including tannins, flavonoids, and anthocyanins, which provide antioxidant and antimicrobial properties, while also facilitating covalent and hydrogen bonding cross-links within the polymer matrix, thus enhancing material durability [107]. The lignocellulose structure, primarily composed of cellulose (30%–40%), hemicellulose (15%–25%), and lignin (15%–20%), offers mechanical support and reactive functional groups (hydroxyl, carboxyl, phenolic) that improve compatibility with bio-based polymers [108,109]. These properties also contribute to the biodegradability of grape leather under aerobic composting conditions, supporting circular economy goals [103]. Natural leather, characterized by its collagen structure and chromium or vegetable tanning, offers high mechanical strength and water resistance but suffers from considerable environmental impacts, including high water consumption, chemical pollution, and greenhouse gas emissions [110,111]. Grape leather utilizes lignocellulosic fibers and abundant polyphenols from grape pomace, delivering moderate tensile strength and flexibility while enhancing biodegradability and minimizing ecological footprint through agro-waste valorization [103,112]. Piñatex, made from pineapple leaf fibers, and Desserto, derived from cactus cellulose, both show comparable mechanical properties and biodegradability with sustainability benefits linked to agricultural by-product usage and low water requirements [113,114]. Mylo, produced from fungal mycelium, is notable for its unique biological structure, fully biodegradable nature, and low environmental burden due to controlled fungal cultivation [111]. Each bio-based leather represents a promising sustainable alternative to conventional leather, balancing functional properties with circular economy principles and reduced environmental impacts.

Table 7: Comparable physical properties of Bio-based leather-like material alternatives

Property	**Natural leather**	**Grape leather**	**Piñatex (Pineapple)**	**Mylo (Mushroom)**	**Desserto (Cactus)**	**References**
Density (g/cm^3)	0.9–1.1	0.8–1.2	~0.9	~0.85	~0.85	[100,115]
Tensile strength (MPa)	15–35	8–25	10–25	8–20	15–30	[74,116,117]
Young's modulus (MPa)	30–100	20–70	20–60	15–50	25–70	[117,118]
Elongation at break (%)	30–70	20–60	25–60	20–50	30–55	[100,116,117]
Water absorption (% after 24 h)	10–20	15–28	20–30	18–25 (treatable)	15–22 (waxes improve)	[116,117]

(Continued)

Table 7 (continued)

Property	Natural leather	Grape leather	Piñatex (Pineapple)	Mylo (Mushroom)	Desserto (Cactus)	References
Biodegradability	Low (synthetic-tanned)	High	High	High	High	[117]
Environmental impact GHG emissions (kg CO_2-eq/m^2)	**22–110**	**4–10**	**2.7–4.0**	2.5–57	1.3–2.0	[117,119]

6 Products Made from Grape Waste, Leather-Like Material

The valorization of grape waste into leather-like biomaterials has enabled the production of a diverse range of sustainable fashion and accessory products, traditionally made from animal leather. Grape pomace, comprising skins, seeds, and stems, is processed and combined with bio-based resins and binders to create materials exhibiting desirable mechanical and aesthetic properties, including flexibility, tensile strength, and abrasion resistance [120,121]. One of the earliest and most widespread applications of grape leather is in small fashion accessories such as wallets, cardholders, and belts. These products benefit from grape leather's soft texture and lightweight characteristics while embodying sustainable practices by using winery by-products [122,123]. The intrinsic polyphenols in grape waste also impart antioxidant and antimicrobial properties, adding functional value to these items [124].

The fashion industry has embraced grape waste leather for handbags and tote bags due to its leather-like appearance and customizable finishes. VEGEA, an Italian pioneer, has commercialized grape marc leather for luxury and mid-tier handbags by blending grape fibers with vegetal resins and eco-friendly binders, achieving a product that rivals animal leather in durability and water resistance after appropriate surface treatments [125,126]. This bio-leather is lightweight, breathable, and can be produced in various colors and textures, meeting consumer demand for sustainable yet stylish products.

Grape waste leather has been incorporated into footwear, including sneakers and casual shoes, where durability and water resistance are critical. Companies such as Pangaia have collaborated with grape leather producers to manufacture eco-conscious sneakers where grape-derived leather is used for uppers, linings, and insoles, enhancing sustainability without compromising performance [105]. However, the use of grape leather in footwear often requires hybridization with other polymers or coatings to improve abrasion resistance and waterproofing [127]. Grape leather's fine grain and flexibility have made it a suitable material for watch straps and belts. These accessories demand materials that combine comfort with tensile strength and longevity. The inherent bioactive compounds in grape leather also contribute to resistance against microbial degradation, extending product life [128,129]. Emerging research explores the use of grape-based leather in automotive interiors and furniture upholstery. Although still in the early stages, grape leather's sustainability credentials and customizable surface properties present promising alternatives to traditional leather and synthetic materials in these sectors summarized in (Table 8) [122,130].

Table 8: Summary of product groups, features, advantages, and limitations

Product group	Key features/ Composition	Advantages	Challenges/ Limitations	Potential applications	References
Vegea®-style sheeted bio-leather	Compressed grape pomace, polymer-coated	Sustainable, natural antioxidants, moderate strength, vegan	Cost of coatings, scalability, and variability of feedstock	Footwear, bags, fashion accessories	[131]
Flexible composite films	Grape pomace + biopolymers (PHA, PLA)	Biodegradable, tunable mechanical properties, natural coloration	Lower tensile strength than synthetic leather, water sensitivity	Apparel lining, book covers, soft goods	[132]
Coated decorative/upholstery panels	Grape waste matrix + protective coatings	Water- and UV-resistant, aesthetic versatility	Coating increases cost and complexity; micro-plastic risk if synthetic polymers are used	Furniture, wall panels, interior design	[132]
Hybrid grape + other lignocellulosic composites	Blends of grape pomace + pineapple fiber or other residues	Enhanced mechanical performance, broader property range	Formulation complexity, process reproducibility, and lack of standards	Footwear, luggage, and interior materials	[133]
Functional apparel leather alternatives	Grape waste + PU/PLA coating, bioactive-rich	Moderate flexibility, antimicrobial, UV-protective	Requires controlled coating application, durability under repeated stress, not fully tested	Jackets, bags, gloves	[134]
Experimental 3D-formed composites	Moulded grape-pomace-based materials	Lightweight, potential for bespoke design	Limited mechanical data, high processing cost	Prototypes, bespoke fashion items	[60]

7 Current Technologies

Recent technological advancements have driven the development of sustainable leather alternatives from diverse sources, including agricultural waste, lab-grown materials, and advanced biopolymers. Agro-industrial by-products such as grape marc, pineapple leaves, and mushroom mycelium are being transformed into leather-like materials through processes that utilize natural polyphenols and fibers for tanning and reinforcement, minimize the use of toxic chemicals, and enhance biodegradability while reducing carbon tracks. Examples include Vegea's patented grape waste leather, produced using water-based binders and dry processing, and Piñatex, which derives its strength from pineapple leaf fibers [135,136]. In parallel, lab-grown and cultured leather technologies leverage cellular agriculture to cultivate animal skin cells into leather sheets without animal slaughter, offering animal welfare benefits, reduced land and water use, and the potential for cellular-level customization, though challenges remain regarding scalability, cost, and matching the performance of traditional leather. Additionally, advanced bio-based synthetic polymers such as polyhydroxyalkanoates (PHA) and polylactic acid (PLA) are being engineered as environmentally friendly alternatives to conventional PU and PVC. When combined with natural fibers, these polymers yield composites with enhanced biodegradability and mechanical properties suitable for leather-like applications [137].

8 The Advantages and Limitations of the Grape Waste Leather-Like Material Alternative

Grape waste leather offers a range of environmental, functional, and aesthetic benefits that make it a promising sustainable material. It valorizes grape pomace, an abundant by-product of winemaking, thus mitigating the environmental impact of agro-industrial waste disposal, including methane emissions from landfills and leachate contamination [138]. Its production process is considerably more eco-friendly than conventional leather tanning, requiring less water and energy and eliminating toxic chromium salts and other hazardous chemicals, thereby lowering greenhouse gas emissions and pollution [83,139]. Additionally, the polyphenolic content of grape pomace provides inherent antioxidant and antimicrobial properties, which can improve material durability and reduce the need for synthetic additives [83]. Composed largely of lignocellulosic fibers and natural polymers, grape leather is biodegradable and compostable, avoiding the long-term environmental persistence characteristic of petroleum-derived synthetic leathers. From a design perspective, it can be engineered with diverse textures and colors derived from anthocyanin, reducing reliance on synthetic dyes and enabling greater aesthetic versatility [120]. These attributes align strongly with circular economy principles by supporting waste-to-value strategies and ethical material sourcing [115]. Despite its potential, grape waste leather faces several technical and commercial challenges. Its mechanical properties, such as tensile strength and abrasion resistance, are generally lower than those of high-grade animal leather, which can limit its suitability for applications requiring high durability, such as automotive upholstery or heavy-duty footwear [140,141]. The hydrophilic nature of lignocellulose fibers makes grape leather susceptible to moisture absorption, swelling, and dimensional instability unless additional coatings or surface treatments are applied; however, these treatments can compromise biodegradability [141]. Scalability is another issue, as grape pomace availability is seasonal and geographically limited to wine-producing regions, which can create supply chain constraints and cost variability [142]. Additionally, the extraction, processing, and fabrication methods required to convert grape waste into uniform, high-quality leather-like materials remain complex and expensive compared to well-established leather manufacturing systems [143]. Finally, consumer awareness and acceptance of grape leather are still limited, posing a challenge to its widespread adoption in mainstream markets [144].

9 Strategies to Overcome the Limitations of Grape Waste Alternative Leather Materials

The valorization of grape waste into bio-based leather-like material alternatives represents a promising avenue for sustainable material innovation; however, inherent limitations such as poor mechanical strength, hydrophobicity, scalability constraints, and inconsistent product quality currently hinder large-scale industrial adoption [145]. Hybridization strategies, in which grape waste is combined with complementary natural fibers, biodegradable polymers, and eco-friendly cross-linkers, have emerged as effective solutions to overcome these challenges. Such hybrid bio-leather systems exploit synergistic interactions among the constituent materials, enabling the tailoring of physicochemical, mechanical, and functional properties beyond what grape waste alone can achieve [146,147]

Mechanical reinforcement is a key focus of hybridization, as tensile strength, elasticity, and abrasion resistance are critical for leather-like applications in fashion, upholstery, and footwear. The intrinsic mechanical limitations of grape waste, largely attributed to its heterogeneous lignocellulosic fiber morphology and weak inter-fiber bonding [148], can be addressed by incorporating high-modulus natural fibers such as hemp, flax, jute, or sisal. These fibers, characterized by highly crystalline cellulose microfibrils with large aspect ratios, function as effective load-bearing reinforcements, improving the overall stiffness and strength of the composite matrix. Enhancing interfacial adhesion between grape waste fibers and reinforcing fibers is critical, and can be achieved through physical surface treatments such as plasma activation or chemical coupling agents like silanes, which improve fiber compatibility and facilitate efficient stress transfer [79].

In addition to fiber reinforcement, blending grape waste with biodegradable polymers such as chitosan, polylactic acid (PLA), polyhydroxyalkanoates (PHA), or polycaprolactone (PCL) has proven effective for mitigating brittleness and improving toughness. These polymers provide a continuous matrix with superior mechanical properties, while also enabling better processing and scalability [145,149]. For instance, chitosan's film-forming ability, biocompatibility, and antimicrobial activity complement the antioxidant properties of grape polyphenols, resulting in hybrid composites with enhanced tensile strength and added functional benefits. The use of natural and synthetic cross-linking agents, including tannins, genipin, and citric acid, further improves the cohesion of hybrid matrices. These agents promote covalent and hydrogen bonding between polymer chains and lignocellulosic fibers, thereby restricting polymer chain mobility and increasing the modulus, tensile strength, and dimensional stability of the resulting composites [145]. Collectively, hybridization strategies significantly advance the mechanical integrity, durability, and functional versatility of grape waste–based leather alternatives, making them more viable for high-performance applications.

10 Future Trends and Research Directions

Future research on sustainable leather-like materials, particularly those derived from agricultural residues such as grape waste, will be driven by rapid advances in biotechnology, green chemistry, and materials science. Cutting-edge studies are expected to focus on optimizing microbial fermentation, enzymatic hydrolysis, and synthetic biology platforms to convert lignocellulosic and polyphenolic-rich grape pomace into high-performance biopolymers. Through genetic engineering and metabolic pathway redesign, microorganisms could be tailored to produce customized extracellular polysaccharides, polyhydroxyalkanoates (PHAs), and bio-based polyurethanes, thereby enhancing tensile strength, elasticity, and biodegradability. Nanotechnology and advanced material functionalization will also play a crucial role in improving the performance of grape waste-derived composites. Incorporation of nano-cellulose, chitin nanofibers, or graphene-based fillers can reinforce mechanical properties, barrier performance, and thermal stability. Moreover, the development of stimuli-responsive smart composites with self-healing, antimicrobial, and moisture-regulating functionalities represents an emerging frontier. Green cross-linking systems such as enzymatic, UV-assisted, or plant-derived polyphenolic approaches are expected to replace conventional petrochemical tanning and finishing agents, minimizing residual toxicity and enhancing biodegradability.

Transitioning from laboratory to industrial scale will require innovations in scalable and energy-efficient processing technologies. Techniques such as extrusion, electrospinning, supercritical CO_2 processing, and microwave-assisted polymerization offer promising routes to improve production efficiency while preserving material integrity. Digital manufacturing technologies, including 3D printing and computer-aided design (CAD), could enable the fabrication of customized textures, thickness profiles, and surface finishes, thereby reducing waste during shaping and cutting operations. To advance grape waste–based leather alternatives toward commercial viability, future research must integrate technical optimization, environmental sustainability, and socio-economic feasibility. Technically, hybridization with natural fibers and biodegradable polymers should be explored to enhance tensile strength, flexibility, and durability, while leveraging the inherent polyphenols, tannins, and seed oils to improve water resistance, UV stability, antimicrobial activity, and natural coloration. Developing scalable, solvent-free, and low-energy extraction and fabrication methods such as enzyme-, ultrasound-, or supercritical CO_2-assisted processes will be essential for sustainable industrial implementation. Standardization of mechanical, barrier, and aging tests will further support reproducibility, quality assurance, and certification.

From a socio-economic perspective, reducing production costs through optimized feedstock pre-processing, cost-efficient coatings, and waste minimization strategies is crucial. Assessing supply chain sustainability, including regional availability, storage stability, and transport of grape pomace, will ensure consistent raw material flow. Additionally, market acceptance studies should evaluate consumer perception related to product aesthetics, tactile quality, and environmental claims. Integrated life cycle assessments and socio-environmental impact analyses will be key to quantifying carbon footprint, water usage, chemical inputs, and overall sustainability performance. Addressing these interlinked technical and socio-economic challenges holistically will enable the transition of grape waste-based leather-like materials from laboratory-scale prototypes to standardized, commercially viable, and truly sustainable leather alternatives.

11 Conclusion

Grape waste-derived leather-like materials, produced from grape pomace a lignocellulosic agro-industrial by-product, offer a sustainable and biodegradable alternative to conventional animal and synthetic leathers. The intrinsic components of grape skins, seeds, and stems, such as polyphenols, tannins, lignin, and waxes, contribute to natural cross-linking, mechanical reinforcement, antioxidant activity, and water resistance, closely replicating traditional vegetable tanning without harmful chemicals. Through eco-friendly extraction, fiber modification, and composite fabrication using bio-based polymers and plasticizers, grape leather can achieve competitive mechanical and aesthetic properties, including tensile strength, flexibility, and surface smoothness.

Despite these advantages, challenges remain regarding mechanical durability, moisture sensitivity, supply scalability, and production cost, which hinder large-scale adoption. Hybrid bio-leather approaches integrating grape waste fibers with other natural fibers and biodegradable polymers have demonstrated potential to improve strength, elasticity, and functionality while maintaining biodegradability. Emerging advancements in biotechnology, nanotechnology, green chemistry, and advanced manufacturing (e.g., enzymatic processing and nano-reinforcements) are expected to further enhance material properties and production efficiency.

Overall, grape waste-based leather-like materials combine moderate mechanical performance, natural antioxidant functionality, and a reduced environmental footprint. However, variability in feedstock composition and processing parameters continues to affect consistency and performance. Future research should prioritize: (1) optimizing material formulations for improved strength, flexibility, and water/UV resistance; (2) developing scalable and eco-efficient fabrication and extraction methods; (3) establishing standardized testing and certification protocols; and (4) addressing economic feasibility, supply chain stability, and consumer acceptance. Overcoming these technical and socio-economic challenges is crucial for advancing grape waste-derived materials from laboratory-scale prototypes to commercially viable, sustainable leather alternatives.

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