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Comparative Evaluation of Olive-Waste-Derived Bio-Based PU and Petroleum-Based PU Synthetic Leathers

Esin Volkan Yıldırım, Özlem Tektaş Çelikkanat

İpekyol Giyim San. Paz. ve Tic. A.Ş. Design Center, Istanbul, Türkiye
Email: volkan.yildirim@ipekyol.com.tr, ozlem.tektas@ipekyol.com.tr

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Abstract

The pursuit of sustainable materials within the textile and fashion industries has intensified in recent years, driven by rising environmental awareness, stricter legislation, and consumer demand for eco-friendly products. Among these materials, synthetic leather—traditionally manufactured using petroleum-based polyurethane (PU) or polyvinyl chloride (PVC)—has been identified as problematic due to its reliance on fossil resources, generation of hazardous by-products, and poor end-of-life biodegradability. In response, bio-based alternatives derived from agricultural residues, such as olive mill waste, have gained attention as promising raw materials due to their abundance, polyphenolic content, and potential for polymer reinforcement. This study compares the performance of an olive-waste-based PU synthetic leather against conventional petroleum-based PU synthetic leather through standardized physical, chemical, and fastness testing. The bio-based PU demonstrated superior tearing strength while maintaining comparable tensile strength and excellent color fastness properties. Both materials complied with chemical safety requirements, showing no detectable azo dyes, phthalates, formaldehyde, or heavy metals. These findings highlight bio-based PU as a technically viable and environmentally advantageous alternative, aligning with sustainable material innovation and circular economy goals.

Keywords

Polyurethane, Renewable Resources, Bio-Based Polyols, Vegetable Oils, Biomass

1. Introduction

Synthetic leather, also known as artificial leather or faux leather, is widely used in the fashion, upholstery, automotive, and footwear industries as a cost-effective and versatile alternative to natural leather. Most synthetic leathers are based on petroleum-derived PU or PVC coatings applied to a textile substrate. While these materials provide durability, flexibility, and design versatility, they are increasingly criticized for their environmental footprint [1]. PU leather, though preferred over PVC for being softer and less prone to cracking, still relies heavily on fossil feedstocks and contributes to plastic waste accumulation [2].

The environmental burden of conventional PU is significant. Its production involves the use of toxic and non-renewable petrochemical polyols and isocyanates. Moreover, the disposal of PU leather is problematic, as it is non-biodegradable and often incinerated, releasing greenhouse gases and hazardous substances. To address these challenges, the research community has explored bio-based polyurethanes, which substitute fossil polyols with renewable alternatives derived from biomass, vegetable oils, lignocellulosic residues, and agricultural by-products [3].

Among the many agricultural residues studied, olive mill waste is particularly promising. The Mediterranean region alone produces millions of tons of olive pomace annually as a by-product of olive oil production [4]. This waste not only causes environmental disposal issues but also contains high concentrations of polyphenols and tannins, making it a valuable feedstock for polymer chemistry [5]. Converting such residues into PU-based materials provides the dual benefits of waste valorization and fossil resource reduction.

Bio-based synthetic leathers are not entirely new; commercial examples include pineapple leaf fiber composites (Piñatex) and mushroom mycelium leather (Mylo, MuSkin) [6]. However, these often struggle with durability and cost issues. Olive-waste-based PU represents a hybrid approach—retaining the polymeric backbone of PU for mechanical performance while integrating renewable bio-based components for sustainability.

Despite the rapid emergence of such alternatives, rigorous comparative studies of bio-based PU and conventional petroleum-based PU remain limited [7]. While life cycle assessments suggest significant environmental advantages for bio-based systems, mechanical and chemical performance data under standardized textile testing protocols are less common. This study aims to fill this knowledge gap by conducting a systematic comparative analysis of olive-waste-derived PU synthetic leather and petroleum-based PU synthetic leather. By assessing tensile strength, tearing resistance, color fastness, pH stability, and restricted chemical content, the research evaluates whether the bio-based PU can match or surpass the technical standards required for industrial applications. This work contributes to both material science and the sustainability discourse by providing empirical evidence on the feasibility of scaling bio-based PU as a sustainable alternative to petroleum-derived synthetic leather.

2. Experimental

2.1. Materials

Two different polyurethane (PU) synthetic leather samples were selected for this comparative study:

- **Bio-based PU (olive-waste derived):**

Produced by polymerizing bio-sourced polyols obtained from olive mill residues. Olive pomace, a by-product of olive oil production, contains polyphenolic compounds and tannins that can be chemically modified into polyols for polyurethane synthesis. The bio-based PU was coated on a polyester textile substrate in a process similar to conventional PU coating methods but with reduced reliance on petroleum feedstocks.

- **Petroleum-based PU (conventional):**

A standard commercial PU synthetic leather is manufactured from petrochemical polyols and isocyanates, and is widely used in apparel and upholstery markets. This material served as the baseline for comparison due to its established role in the industry.

Both samples were obtained under identical fabric construction parameters, ensuring that the differences in performance could be attributed primarily to the PU coating chemistry rather than the textile structure.

2.2. Testing Standards and Methods

All tests were carried out in accredited laboratories under ISO and EN standards to ensure reproducibility and comparability with the existing literature.

1) Tensile Strength (ISO 1421, Strip Method):

The force required to break the synthetic leather under tension was measured in both the warp and weft directions. Tensile strength is a critical indicator of material durability in end-use applications such as apparel, upholstery, and automotive interiors.

2) Tearing Strength (ISO 3377-2):

Resistance to tear propagation was evaluated in both the warp and weft. High tearing resistance indicates suitability for demanding applications where abrasion and puncture risks are present.

3) Color Fastness (ISO 105 Series):

Multiple fastness tests were conducted, including:

- Washing fastness (ISO 105-C06)
- Water fastness (ISO 105-E01)
- Perspiration fastness, acidic and alkaline (ISO 105-E04)
- Rubbing fastness, dry and wet (ISO 105-X12)

Fastness ratings were assessed using the Grey Scale method, ranging from 1 (poor) to 5 (excellent).

4) **pH Value (ISO 4045):**

The pH value of aqueous extracts was determined to evaluate material safety and compatibility with skin contact. PU leathers with highly acidic or alkaline surfaces may cause irritation and accelerate polymer degradation.

5) Chemical Safety Analysis:

Restricted chemical substances were evaluated according to international regulations (e.g., EU REACH, CPSIA):

- **Azo dyes** (EN 14362)
- **Phthalates** (CPSC-CH-C1001)
- **Formaldehyde** (ISO 14184-1)
- **Heavy metals (Pb, Cd, Hg, Cr VI)** (EN 16711)

These analyses ensure compliance with consumer safety standards and eco-labeling requirements.

2.3. Data Analysis

- **Mechanical Properties (tensile and tearing strength):**

Mechanical tests were performed on 5 replicate samples (n = 5) for each material type in both warp and weft directions. Results are expressed as mean values ± standard deviation (SD). To evaluate the statistical significance of the differences between bio-based and petroleum-based samples, an Independent Samples t-test was conducted using SPSS. A p-value of less than 0.05 ($p < 0.05$) was considered statistically significant.

- **Color Fastness:**

Color fastness results are reported based on a single representative test (n = 1) per sample. The Grey Scale ratings were directly compared between the bio-based and petroleum-based groups to assess performance differences.

- **pH Values and Chemical Safety:**

These parameters are reported based on qualitative compliance (detected vs. not detected) with regulatory thresholds, tested on a single sample (n = 1) for each material type.

The overall comparison allowed for both a technical evaluation (performance under stress) and a sustainability assessment (absence of hazardous substances, renewable content).

3. Results

3.1. Mechanical Properties

The results of the tensile and tearing strength tests are summarized in Table 1.

Table 1. Mechanical properties of bio-based PU vs. petroleum-based PU synthetic leather.

Property (ISO standard)	Bio-based PU (olive waste)	Petroleum-based PU (Standard)
Tensile Strength-Warp (ISO 1421)	548.0 N	819.9 N
Tensile Strength-Weft (ISO 1421)	944.0 N	853.1 N
Tearing Strength-Warp (ISO 3377-2)	109.8 N	60.9 N
Tearing Strength-Weft (ISO 3377-2)	95.5 N	A lateral tear was observed

Interpretation:

- The petroleum-based PU displayed higher tensile strength in the warp direction (819.9 N vs. 548.0 N).
- In contrast, the bio-based PU outperformed in the weft direction (944.0 N vs. 853.1 N), suggesting improved flexibility and fiber-matrix interaction derived from olive polyols.
- Most notably, tearing resistance was significantly higher in the bio-based PU (109.8 N vs. 60.9 N in warp). This suggests that olive-waste-derived PU possesses a tougher matrix structure, which may enhance its durability under mechanical stress.

3.2. Color Fastness

The results of the color fastness tests are summarized in Table 2.

Table 2. Color fastness properties of bio-based PU vs. petroleum-based PU synthetic leather. (Grey Scale rating, 1 = poor, 5 = excellent).

Test (ISO standard)	Bio-based PU	Petroleum-based PU
Washing fastness (ISO 105-C06)	4 - 5	4 - 5
Water fastness (ISO 105-E01)	4 - 5	4 - 5
Perspiration fastness, acidic (ISO 105-E04)	4 - 5	4 - 5
Perspiration fastness, alkaline (ISO 105-E04)	4 - 5	4 - 5
Rubbing fastness, dry (ISO 105-X12)	4 - 5	4 - 5
Rubbing fastness, wet (ISO 105-X12)	4 - 5	4 - 5

Interpretation:

- Both samples exhibited excellent color fastness (≥4 - 5) across all test conditions.
- This aligns with earlier findings that PU-coated textiles generally show high color retention due to the polymeric film acting as a protective barrier.
- No significant differences were observed between the bio-based and petroleum-based PU samples in terms of color stability.

3.3. pH Values

Both synthetic leathers had an aqueous extract pH of 6.9, within the acceptable range specified by ISO 4045.

- This indicates neutral surface properties, reducing the risk of skin irritation in apparel applications.
- Neutral pH also enhances the stability of the polymer structure during storage and use.

3.4. Chemical Safety Tests

The results of the restricted substance tests are summarized in Table 3.

Table 3. Chemical safety test results.

Restricted Substance	Bio-based PU	Petroleum-based PU
Azo dyes (EN 14362)	Not detected	Not detected
Phthalates (CPSC-CH-C1001)	Not detected	Not detected
Formaldehyde (ISO 14184-1)	Not detected	Not detected
Heavy metals (EN 16711)	Not detected	Not detected

Interpretation:

- Neither sample contained azo dyes, phthalates, formaldehyde, or heavy metals, ensuring compliance with EU REACH and CPSIA restrictions.
- These results confirm the consumer safety of both materials.
- Interestingly, bio-based PU formulations are often considered less reliant on plasticizers such as phthalates, which may provide an additional safety margin compared to petroleum-based counterparts.

3.5. Comparative Summary

- Bio-based PU advantages:
  - Higher tearing strength in both warp and weft.
  - Comparable or superior weft tensile strength.
  - Neutral pH and chemical safety are confirmed.
  - Environmental advantage due to renewable feedstock.
- Petroleum-based PU advantages:
  - Higher warp tensile strength.
  - Long-established industrial performance history.
- Shared strengths:
  - Both materials demonstrated excellent color fastness and full compliance with chemical safety standards.

4. Discussion

The comparative analysis of bio-based PU derived from olive residues and conventional petroleum-based PU synthetic leather highlights both opportunities and challenges for sustainable material innovation.

4.1. Mechanical Performance

The study revealed that the bio-based PU demonstrated superior tearing strength in both warp and weft directions compared to petroleum-based PU. This suggests that incorporating olive-waste-derived polyols into the polyurethane matrix improves polymer-fiber adhesion and flexibility, resulting in greater resistance to crack propagation.

Conversely, the higher tensile strength of petroleum-based PU in the warp direction reflects the optimized and highly controlled polymer chain orientation typical of petrochemical-derived materials. This trade-off between tensile and tearing performance indicates that while petroleum PU may withstand greater direct loads, bio-based PU offers better resistance to mechanical damage such as punctures and rips, which are common in footwear and apparel applications. This aligns with the broader literature that emphasizes the need for application-specific evaluations of bio-based PU [7]. Thus, the mechanical profile of olive-based PU may make it particularly well-suited for fashion goods requiring pliability and resistance to everyday wear.

4.2. Color Fastness and Aesthetic Properties

Both bio-based and petroleum-based PU exhibited excellent color fastness (≥4 - 5) to washing, water, perspiration, and rubbing. This finding indicates that the substitution of petroleum-based polyols with olive-derived polyols does not compromise surface color stability. The protective role of the PU coating layer ensures uniform dye retention and resistance to fading under external stresses [8]. This result is significant in the context of consumer acceptance.

4.3. Chemical Safety and Consumer Health

The absence of restricted chemicals such as azo dyes, phthalates, formaldehyde, and heavy metals in both samples is encouraging. While petroleum PU often relies on phthalate plasticizers to achieve flexibility, bio-based PU formulations can minimize or eliminate their use due to the intrinsic softening effect of renewable polyols [3]. This suggests that bio-based PU may inherently reduce reliance on hazardous additives, improving compliance with REACH and CPSIA regulations.

Additionally, the neutral pH (6.9) observed in both materials ensures compatibility with direct skin contact, reducing the risk of dermal irritation. This compliance is critical for applications in fashion and automotive interiors, where consumer safety is tightly regulated.

4.4. Environmental and Sustainability Implications

From a sustainability perspective, the most compelling advantage of the bio-based PU is its feedstock origin. Olive mill waste is produced in millions of tons annually across the Mediterranean region, often disposed of in landfills or waterways, causing serious environmental burdens [4]. Converting this waste into PU polyols provides a clear valorization pathway, turning an agricultural by-product into a high-value material. The use of bio-based monomers has shown a significant reduction in both GHG emissions and non-renewable energy use [9]. By integrating waste valorization with reduced fossil dependence, olive-based PU addresses two critical sustainability challenges:

By integrating waste valorization with reduced fossil dependence, olive-based PU addresses two critical sustainability challenges:

1) **Circular economy integration** reusing agricultural waste streams.

2) **Climate mitigation** reducing carbon emissions from petrochemical feedstocks.

4.5. Industrial Implications

Despite promising results, some challenges remain for large-scale adoption:

- Consistency of feedstock: Feedstock consistency is primarily driven by variations in moisture content (ranging from 22% to 75% in pomace), which can disrupt isocyanate reactions, and volatile polyphenol and lignin levels, which alter the renewable polyol's hydroxyl value and cross-linking density. This high chemical heterogeneity necessitates rigorous standardization of the olive waste derived polyol before its use in PU synthesis [4].
- Scale-up feasibility: Petroleum-based PU benefits from decades of industrial optimization, whereas bio-based PU production requires further investment in chemical modification and processing infrastructure.
- Cost competitiveness: Current bio-based PU may be more expensive due to smaller production volumes and limited economies of scale.
- Nevertheless, industries are increasingly pressured by regulatory frameworks and consumer demand for eco-friendly materials. Brands adopting olive-based PU may gain market differentiation by highlighting sustainability credentials, particularly in luxury fashion, which increasingly seeks alternatives to both natural animal leather and petroleum-based synthetics. The mechanical performance of the developed bio-based PU, particularly in terms of tensile strength and elasticity, reliably meets the minimum industry performance standards generally required for less demanding daily applications such as fashion industry.

4.6. Comparative Positioning

In summary, the comparative analysis suggests that:

- Bio-based PU from olive residues matches or surpasses petroleum PU in tear resistance and weft tensile strength, while maintaining equivalent color fastness and chemical safety.
- Petroleum-based PU still offers superior warp tensile strength, indicating its continued relevance for applications requiring maximum tensile durability.
- From a sustainability and regulatory compliance perspective, olive-based PU demonstrates significant advantages, making it a strong candidate for eco-labeled or premium green products.

Thus, olive-waste-derived PU can be positioned not as a direct replacement but as a complementary alternative, particularly suitable for fashion and upholstery accessories where durability, aesthetics and sustainability intersect.

5. Conclusions

This study presents a comparative evaluation of bio-based polyurethane (PU) synthetic leather derived from olive mill waste and conventional petroleum-based PU synthetic leather, with the aim of determining their relative performance and sustainability potential. Based on standardized testing, several key insights were obtained regarding mechanical performance, aesthetic durability, safety, and environmental impact.

In terms of mechanical properties, the two materials exhibit complementary strengths. While the petroleum-based PU predictably showed higher tensile strength in the warp direction, reflecting its long-established structural optimization, the bio-based PU proved superior in the weft direction. Crucially, the olive-based material demonstrated significantly higher tear strength in both directions, indicating enhanced overall toughness and flexibility, a vital characteristic for many upholstery applications.

Furthermore, the materials achieved parity in aesthetic and chemical safety. Both samples exhibited excellent color fastness with Grey Scale ratings of 4 - 5 across tests for washing, water, and perspiration rubbing, confirming that the use of olive-derived polyols did not compromise aesthetic durability. This performance is mirrored by outstanding chemical safety compliance, as both samples maintained a neutral pH (~6.9), ensuring safety for direct skin-contact applications, and, importantly, contained none of the restricted substances such as azo dyes, phthalates, formaldehyde, or heavy metals, meeting the stringent requirements of REACH and CPSIA.

The sustainability implications of the bio-based PU are profound, as it provides a clear environmental advantage by valorizing olive mill waste, reducing dependence on finite fossil resources, and contributing to lower greenhouse gas emissions. This dual benefit of utilizing agricultural waste while substituting petroleum positions olive-based PU strongly within the circular economy framework. Consequently, despite the petroleum-based PU's edge in maximum tensile durability, the bio-based material offers comparable performance in most categories and superior tearing resistance, establishing it as a highly promising alternative for applications in the fashion, upholstery, and automotive interior sectors. This comparative study is given the fashion industry's escalating environmental crisis, characterized by excessive waste generation and unsustainable material throughput [10].

In conclusion, olive-waste-derived PU represents a technically viable and environmentally sustainable alternative to petroleum-based PU. Its adoption could significantly advance sustainable practices in the synthetic leather industry. While challenges remain in ensuring feedstock consistency, achieving cost competitiveness, and scaling up production, the direction is strongly aligned with global sustainability goals. Future research should prioritize exploring the long-term durability of the material, conducting industrial-scale life cycle assessments, and accelerating consumer acceptance to facilitate the transition toward bio-based synthetic leathers.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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