

Binder Engineering of Leather Shaving Waste–Based Collagen Composite for Shoe Insole Application: Mechanical–Moisture Trade-Off Analysis

Rekayasa Binder pada Komposit Kolagen Berbasis Limbah Serutan Kulit untuk Aplikasi Insole Sepatu: Analisis Trade-Off Mekanik–Kelembapan

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ABSTRACT

Leather shaving waste (LSW) generated from the tannery industry contains chromium-stabilized collagen fibers that are environmentally persistent and difficult to manage. This study investigates the valorization of LSW into leather board for shoe insole applications through binder system engineering. LSW was neutralized using alkaline treatment and compounded with polyester resin and polyvinyl acetate (PVAc), followed by press molding. Mechanical properties and water absorption were evaluated according to SNI 1294-2009 standards. The results show that binder composition influences interfacial interactions, mechanical properties, and moisture behavior of the composites. Formulation F3 exhibited the highest tensile and tear strength, while formulation F4 showed lower water absorption compared to other formulations. An Engineering Performance Index (EPI) was introduced to integrate mechanical strength and moisture resistance, revealing a trade-off between mechanical performance and water sensitivity. Formulation F6 presented a more balanced mechanical–moisture profile, with properties comparable to the commercial product, indicating its potential for practical insole applications under moderate conditions. These findings suggest that binder system design plays an important role in controlling the structure–property relationship of collagen-based composites and provides a potential pathway for the sustainable utilization of tannery solid waste.

Keywords: leather shaving waste, collagen composite, binder engineering, structure–property relationship, sustainable materials.

ABSTRAK

Limbah serutan kulit (leather shaving waste/LSW) yang dihasilkan dari industri penyamakan mengandung serat kolagen yang distabilkan oleh kromium, sehingga bersifat persisten di lingkungan dan sulit dikelola. Penelitian ini mengkaji pemanfaatan LSW menjadi papan kulit (leather board) untuk aplikasi insole sepatu melalui rekayasa sistem binder. LSW dinetralkan menggunakan perlakuan alkali dan dikompositkan dengan resin poliester dan polivinil asetat (PVAc), kemudian dicetak menggunakan metode press molding. Sifat mekanik dan penyerapan air dievaluasi sesuai standar SNI 1294-2009. Hasil penelitian menunjukkan bahwa komposisi binder memengaruhi interaksi antarmuka, sifat mekanik, serta perilaku kelembapan dari komposit. Formulasi F3 menunjukkan kekuatan tarik dan sobek tertinggi, sedangkan formulasi F4 menunjukkan penyerapan air yang lebih rendah dibandingkan formulasi lainnya. Indeks Kinerja Rekayasa (Engineering Performance Index/EPI) diperkenalkan untuk

mengintegrasikan kekuatan mekanik dan ketahanan terhadap kelembapan, yang menunjukkan adanya trade-off antara performa mekanik dan sensitivitas terhadap air. Formulasi F6 menunjukkan profil mekanik–kelembapan yang lebih seimbang, dengan sifat yang sebanding dengan produk komersial, sehingga berpotensi untuk aplikasi insole dalam kondisi penggunaan sedang. Temuan ini menunjukkan bahwa desain sistem binder berperan penting dalam mengendalikan hubungan struktur–sifat pada komposit berbasis kolagen serta memberikan peluang untuk pemanfaatan limbah padat industri penyamakan secara berkelanjutan.

Kata kunci: limbah serutan kulit, komposit kolagen, rekayasa binder, hubungan struktur–sifat, material berkelanjutan.

INTRODUCTION

The leather tanning industry generates significant quantities of solid waste, particularly leather shaving waste (LSW), which consists primarily of collagen fibers containing chromium residues. Due to its crosslinked collagen structure and chromium stabilization, LSW is resistant to natural degradation and poses environmental risks if disposed of improperly. Therefore, converting LSW into value-added composite materials represents a promising sustainable solution.

Natural fiber–reinforced polymer composites have been extensively studied over the past two decades as environmentally friendly alternatives to synthetic composites. According to Faruk et al. (2012), the development of biocomposites reinforced with natural fibers has shown significant growth due to their low density, biodegradability, renewability, and acceptable mechanical performance (Faruk et al., 2012). Similarly, Bledzki and Gassan (1999) emphasized that cellulose-based fibers can effectively

enhance stiffness and strength when properly bonded with polymer matrices (Bledzki and Gassan, 1999).

Collagen-based leather fibers exhibit structural similarities to plant-based natural fibers in terms of reinforcing capability. However, their hydrophilic nature and surface chemistry strongly influence interfacial adhesion and moisture sensitivity. John and Thomas (2008) reported that the performance of biofiber composites is highly dependent on fiber–matrix compatibility, surface polarity, and chemical interactions at the interface (John and Thomas, 2008). In leather materials, the collagen fiber network contains abundant polar functional groups such as amide (–CONH–), carboxyl (–COOH), and hydroxyl (–OH), which contribute to strong water affinity and influence mechanical behavior as well as bonding with polymeric binders (Hermawan et al., 2023).

The mechanical properties of natural fiber composites are largely governed by interfacial bonding and stress transfer efficiency. A comprehensive review by

Pickering et al. (2016) demonstrated that inadequate interfacial adhesion leads to premature failure due to fiber pull-out and debonding (Pickering et al., 2016). Furthermore, Ku et al. (2011) highlighted that tensile performance is strongly influenced by matrix rigidity, fiber dispersion, and processing conditions (Ku et al., 2011). Similar behavior has been reported in leather materials, where the arrangement and bonding of collagen fibers significantly affect tensile strength, elongation, and resistance to mechanical stress (Hermawan et al., 2023).

Moisture absorption remains one of the main challenges in bio-based composites. Dhakal et al. (2007) reported that water absorption significantly reduces tensile strength in hemp fiber-reinforced polyester composites due to matrix plasticization and interfacial weakening (Dhakal et al., 2007). This phenomenon is particularly relevant for collagen-based leather waste, which inherently contains polar amide groups.

Chemical modification and alkaline treatment are commonly applied to improve interfacial bonding and reduce hydrophilicity. Alkaline-based processes, such as the use of lime suspension and lime water in leather processing, have also been reported as effective approaches to enhance fiber cleanliness and support cleaner production practices (Winata and

Hermawan, 2025). Mwaikambo and Ansell (2002) demonstrated that alkalization improves surface roughness and promotes better mechanical interlocking (Mwaikambo and Ansell, 2002). In addition, Kabir et al. (2012) explained that surface treatment enhances compatibility between hydrophilic fibers and hydrophobic polymer matrices (Kabir et al., 2012). Surface morphology and fiber chemistry play a dominant role in composite performance. Sgriccia et al. (2008) emphasized that fiber surface characteristics directly affect stress transfer mechanisms and composite durability (Sgriccia et al., 2008).

Recent studies have explored leather waste as reinforcement in polymer composites. Sharma et al. (2023) reported successful fabrication of polymer composites using leather waste fibers and recycled EVA, showing potential for value-added applications (Sharma et al., 2023). More recently, Khan et al. (2025) demonstrated the feasibility of eco-friendly composites derived from leather waste with competitive mechanical properties (Khan et al., 2025). Additionally, Ajayi et al. (2025) highlighted the growing interest in sustainable natural fiber-reinforced polymer systems for structural and semi-structural applications (Ajayi et al., 2025).

Despite increasing interest in leather waste valorization, limited studies

systematically evaluate the mechanical–moisture trade-off in collagen-based composites derived from tannery solid waste. Most studies emphasize maximum strength without considering durability stability under humid conditions. Therefore, this study introduces an Engineering Performance Index (EPI) to provide an integrated evaluation of tensile strength, tear resistance, and water absorption. By analyzing the structure–property relationship governed by binder composition, this work aims to clarify how mechanical performance and hydrophilic stability can be balanced for practical footwear applications.

MATERIALS AND METHODS

Materials

Chromium-containing leather shaving waste (LSW) was collected from a local tannery in Yogyakarta, Indonesia. Polyester resin, polyvinyl acetate (PVAc) adhesive (fox glue), latex adhesive, and natural turmeric dye were used as binder components without further purification. Sodium hydroxide (NaOH, analytical grade) and distilled water were used for neutralization and washing processes. All materials were used as received without further purification.

Preparation of Leather Shaving Waste

LSW was washed twice with distilled water to remove surface impurities. The material was then soaked in distilled water containing 10% NaOH solution for 24 h to neutralize residual acidic compounds and improve fiber surface characteristics. After decantation, LSW was rinsed repeatedly with distilled water until neutral pH was achieved. The treated LSW was oven-dried at 35 °C until constant weight and stored in sealed containers prior to use.

Formulation Design

Six different formulations (F1–F6) were prepared to evaluate the effect of binder composition on mechanical and moisture properties. The detailed composition of each formulation is presented in Table 1. The LSW and polyester resin contents were kept constant, while the proportions of latex glue, PVAc (fox glue), dyestuff, and natural turmeric dye were varied to investigate their influence on interfacial adhesion and water sensitivity. All formulations (F1–F6) were prepared under identical processing conditions to ensure consistency in sample fabrication.

Table 1. Composition of leather board formulations (F1–F6).

Materials	F1	F2	F3	F4	F5	F6
LSW (g)	30	30	30	30	30	30
Polyester resin (g)	30	30	30	30	30	30
Latex adhesive (mL)	30	30	–	–	–	–

PVAc adhesive (mL)	–	–	30	30	–	–
Synthetic dyestuff (g)	2	–	2	–	2	–
Natural turmeric dye (g)	–	2	–	2	–	2

Composite Fabrication

Dried LSW was mixed with binder components according to formulations F1–F6 (Table 1) using an overhead mixer at 500 rpm for 15 min to ensure homogeneous dispersion of collagen fibers within the polymeric matrix.

The mixture was poured into a steel mold and subjected to press molding at 8 MPa for 15 min at room temperature ($\sim 30\text{ }^{\circ}\text{C}$). This process promotes fiber compaction, reduces void content, and enhances interfacial contact between collagen fibers and the binder system.

The molded sheets were then removed and cured at $30\text{ }^{\circ}\text{C}$ for 12 h until constant weight was achieved. This curing process allows binder solidification and structural stabilization of the composite through polymer network formation, particularly within the polyester resin phase.

All samples were conditioned at room temperature ($27 \pm 2\text{ }^{\circ}\text{C}$) prior to testing to ensure moisture equilibrium.

In terms of composition, LSW and polyester resin were maintained at a 1:1 weight ratio, corresponding to

approximately 50 wt% each in the solid fraction. The liquid binders (latex and PVAc adhesives) were added at a fixed volume of 30 mL. Based on typical densities (latex $\approx 0.95\text{ g/cm}^3$; PVAc $\approx 1.05\text{ g/cm}^3$), this corresponds to approximately 28–32 g of additional binder, resulting in a semi-wet composite mixture prior to molding.

The LSW particles consisted of irregular fibrous structures with an approximate size range of 0.5–2 mm, as obtained from the shaving process without further sieving.

The cured composite sheets were cut into test specimens according to SNI 1294-2009 standard dimensions for tensile, elongation, and tear testing. The fabricated leather board and its application as a shoe insole are shown in Figure 1.

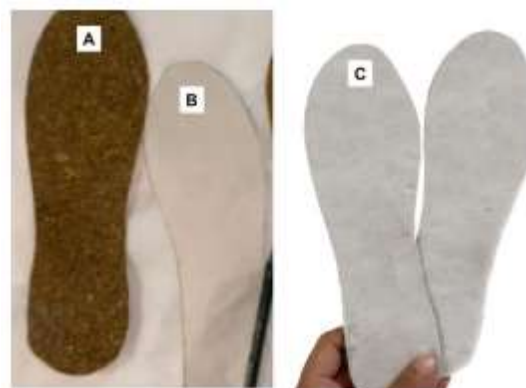


Figure 1. (a) Fabricated leather board sheet produced from LSW composite; (b) Commercial insole used as reference; (c) Insole prototype prepared from LSW-based leather board.

Mechanical Testing

Mechanical testing (tensile strength, elongation, and tear strength) was conducted for each formulation (F1–F6) under controlled and identical conditions due to material and processing constraints. The measurements were performed in accordance with SNI 1294-2009, following procedures reported in previous studies (Juhana et al., 2020). The obtained values are presented as comparative data to evaluate performance trends among different formulations.

Although formal replication was limited, each measurement was repeated until stable and consistent values were obtained, ensuring data reliability.

Water Absorption Test

Due to material and processing constraints, replicate measurements were not performed in this study. However, all experimental parameters were strictly controlled to ensure consistency and comparability among formulations. Therefore, the results are interpreted as indicative of comparative trends rather than statistically validated values.

Although formal replication was limited, each measurement was repeated until stable and consistent values were obtained, ensuring data reliability

RESULTS AND DISCUSSION

Table 2 presents the raw measured values of mechanical and physical properties for

all formulations (F1–F6) and the commercial product (CP). Since the measurements were conducted without full statistical replication, the results are interpreted based on comparative trends rather than statistical significance. However, each measurement was repeated until stable and consistent values were obtained, ensuring data reliability.

Although statistical analysis (e.g., standard deviation and ANOVA) was not performed due to experimental constraints, all processing parameters and testing conditions were strictly controlled to ensure consistency and comparability among formulations. Therefore, the data are considered as preliminary but meaningful indicators for evaluating the influence of binder composition on composite performance

Effect of Binder System on Tensile Strength

The tensile performance of the developed leather board composites is strongly influenced by binder polarity and interfacial adhesion. Polyester resin primarily provides structural rigidity through the formation of a crosslinked thermoset network, whereas polyvinyl acetate (PVAc) contributes polar acetate groups capable of interacting with collagen fibers.

From a chemical perspective, the tensile enhancement observed in PVAc-containing

formulations can be attributed to intermolecular interactions between the acetate groups ($-\text{OCOCH}_3$) of PVAc and the amide functional groups ($-\text{CONH}-$) present in collagen. These interactions are theoretically consistent with hydrogen bonding mechanisms commonly reported in biopolymer-based composites (John and Thomas, 2008; Kabir et al., 2012). In such systems, the carbonyl oxygen of PVAc can act as a hydrogen bond acceptor, while the amide hydrogen in collagen serves as a donor, promoting improved interfacial adhesion and stress transfer across the fiber–matrix interface.

However, it should be noted that the present study does not include direct spectroscopic (e.g., FTIR) or microscopic (e.g., SEM) characterization to explicitly confirm these interactions or to visualize interfacial morphology. Therefore, the proposed hydrogen bonding interactions and interfacial phenomena should be understood as mechanism-based interpretations derived from established chemical principles and supported by previous studies (Pickering et al., 2016; Sgriccia et al., 2008). Similar approaches are widely accepted in composite material research, where structure–property relationships are inferred from mechanical performance trends and known material chemistry.

Future work is recommended to include FTIR analysis to detect potential shifts in amide I and amide II bands, as well as SEM imaging to provide direct evidence of interfacial bonding and pore structure. Despite these limitations, the consistency between the observed mechanical–moisture behavior and established theoretical frameworks supports the validity of the proposed interpretations. A schematic representation of the molecular interaction between PVAc and collagen is proposed (Figure 2), where PVAc chains act as molecular bridges that anchor collagen fibers, thereby enhancing interfacial adhesion and load transfer efficiency. Similar improvements in adhesion within leather systems have been reported when reactive functional groups interact with collagen structures, resulting in stronger interlayer bonding (Hermawan et al., 2023). In contrast, polyester resin contributes mainly through the formation of a rigid crosslinked network with relatively lower polarity compared to PVAc. Therefore, the combination of polar interactions (hydrogen bonding) and mechanical interlocking is considered to enhance stress transfer efficiency, particularly in formulation F3.

The tensile strength results show a clear variation among the formulations, as presented in Table 2. Formulation F3 exhibited the highest tensile strength (3.048

N/mm²), followed by F4 (2.081 N/mm²), indicating that PVAc-containing systems significantly enhance load transfer efficiency within the composite structure. In contrast, F5 showed the lowest tensile strength (0.348 N/mm²), suggesting inadequate interfacial bonding and inefficient stress transfer between collagen fibers and the binder matrix.

Compared with the commercial product (CP, 0.552 N/mm²), formulations F1–F4 demonstrated superior tensile performance, while F6 (0.531 N/mm²) showed a comparable value. This indicates that optimized binder compositions are capable of achieving mechanical properties equivalent to or exceeding those of conventional insole materials.

The enhanced tensile behavior observed in F3 is attributed to improved interfacial interaction between collagen fibers and the PVAc binder, which promotes more efficient stress transfer across the composite structure. Overall, these findings confirm that binder polarity and interfacial compatibility play a critical role in determining the tensile performance of LSW-based collagen composites.

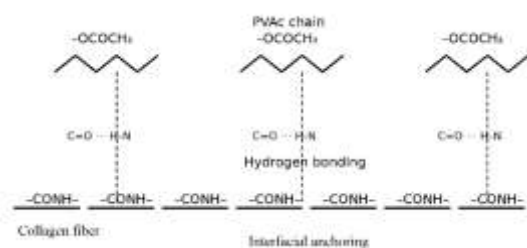


Figure 2. Proposed interaction mechanism between binder components and collagen fibers in LSW-based composites.

The values presented in Table 2 serve as the basis for evaluating the influence of binder composition on mechanical and physical properties of the composites. Table 2 presents the raw measured values of mechanical and physical properties for all formulations (F1–F6) and the commercial product (CP). These data are used as the basis for comparative analysis in the following discussion.

Table 2. Mechanical and physical properties of LSW-based composites (F1–F6) compared with commercial product (CP)

Formulation	Tensile Strength (N/mm ²)	Elongation (%)	Tear Strength (N/mm)	Hardness (Shore A)	Water Absorption (%)
F1	1.2	0.44	1.8	74.6	67
	20	4	67		
F2	1.2	0.44	2.8	81.2	66
	52	4	94		
F3	3.0	5.94	5.1	70.5	69
	48	1	92		
F4	2.0	4.69	4.3	74.5	64
	81	2	93		
F5	0.3	0.44	0.8	60.0	115
	48	4	71		
F6	0.5	0.44	1.1	58.9	85
	31	4	82		

CP	0.5	0.44	0.8	27.7	37
	52	4	11		

Note: Values represent single measurements for each formulation without replication.

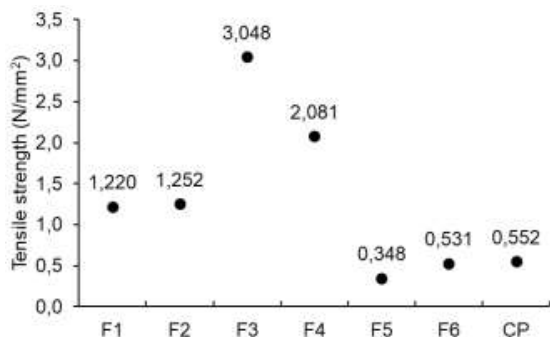


Figure 3. Tensile strength of LSW-based leather board formulations (F1–F6) compared with commercial product (CP).

This behavior is consistent with the interfacial adhesion mechanism described by Pickering et al. (2016), where strong fiber–matrix bonding enhances load transfer efficiency (Pickering et al., 2016). Furthermore, Ku et al. (2011) noted that uniform fiber dispersion and matrix continuity are critical in maximizing tensile properties (Ku et al., 2011). In this study, mechanical improvement is attributed to improved stress transfer efficiency and reduced interfacial defects.

Overall, these findings confirm that binder polarity and interfacial compatibility play a critical role in determining the tensile performance of LSW-based collagen composites. The consistency of trends across all formulations suggests that the observed differences are systematic rather than random..

Elongation and Flexibility Behavior

Elongation at break reflects the flexibility and ductility of the composite material.

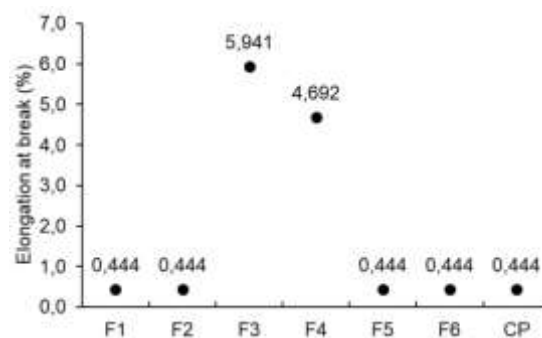


Figure 4. Elongation at break of LSW-based leather board formulations (F1–F6) compared with commercial product (CP).

As presented in Table 2, most formulations (F1, F2, F5, and F6) exhibited relatively low elongation values (0.444%), indicating limited deformability and more brittle behavior. In contrast, F3 (5.941%) and F4 (4.692%) showed significantly higher elongation, suggesting enhanced flexibility. The improved elongation observed in F3 and F4 can be attributed to more effective binder distribution and improved fiber–matrix interaction, which reduce stress concentration and delay crack initiation. The presence of PVAc in these formulations likely contributes to increased ductility by promoting a more flexible polymer network within the composite structure.

This behavior is advantageous for applications requiring a balance between strength and flexibility, such as shoe insoles, where resistance to repeated

deformation is essential for user comfort and durability.

John and Thomas (2008) emphasized that biofiber composites often suffer brittleness when matrix crosslink density is excessively high. Therefore, optimizing binder ratio is essential to maintain balance between stiffness and elongation.

Tear Strength and Structural Integrity

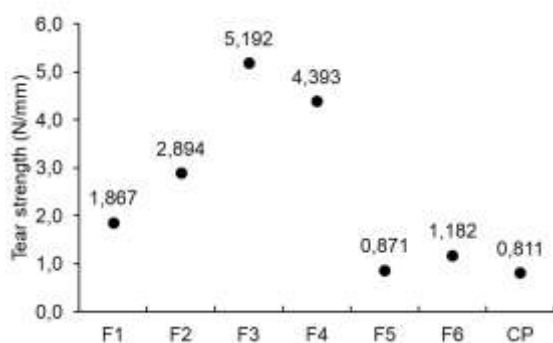


Figure 5. Tear strength of LSW-based leather board formulations (F1–F6) compared with commercial product (CP).

Tear strength results, as presented in Figure 5, further confirm the influence of binder composition on the structural integrity of the composites. Formulation F3 exhibited the highest tear strength (5.192 N/mm), followed by F4 (4.393 N/mm) and F2 (2.894 N/mm), while F5 showed the lowest tear resistance (0.871 N/mm).

Compared to the commercial product (0.811 N/mm), all formulations except F5 demonstrated higher tear strength, indicating improved resistance to crack propagation.

The superior tear performance observed in F3 and F4 suggests effective stress

distribution and strong fiber–matrix interactions, which enhance resistance to crack initiation and propagation. This behavior is closely associated with improved crack deflection and energy dissipation mechanisms within the composite structure.

Bledzki and Gassan (1999) reported that natural fiber reinforcement can effectively bridge cracks when sufficient interfacial bonding is achieved. Therefore, the improved tear strength in optimized formulations indicates effective load transfer between fibers and matrix, contributing to better structural continuity and resistance to mechanical failure.

Hardness and Structural Balance

Hardness values reflect the rigidity and comfort characteristics of the composite materials. As presented in Table 2, hardness values ranged from 58.9 Shore A (F6) to 81.2 Shore A (F2), while the commercial product exhibited a significantly lower value of 27.7 Shore A, indicating a much softer material.

Among the developed formulations, F6 (58.9 Shore A) demonstrated the closest hardness to practical insole requirements, suggesting a more favorable balance between structural support and user comfort. In contrast, the higher hardness values observed in F1–F4 indicate stiffer materials, which may reduce comfort during prolonged use.

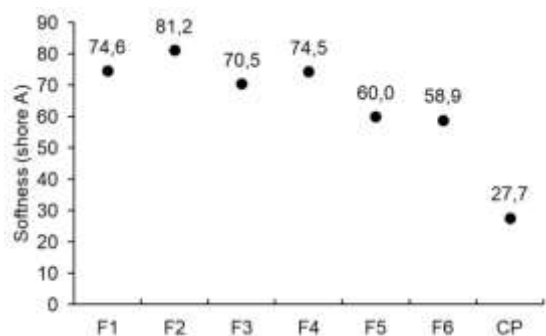


Figure 6. Shore A hardness of LSW-based leather board formulations (F1–F6) and commercial product (CP).

Achieving balanced rigidity is essential for footwear applications, as excessive stiffness may compromise comfort while insufficient stiffness reduces durability..

Water Absorption Behavior

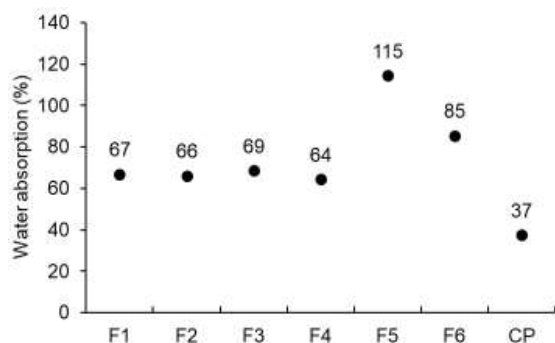


Figure 7. Water absorption of LSW-based leather board formulations (F1–F6) and commercial product (CP) after 24 h immersion.

Water absorption behavior is a critical factor for footwear applications. As presented in Figure 7, formulation F4 exhibited the lowest water absorption (64%), followed by F2 (66%) and F1 (67%). In contrast, F5 showed the highest water uptake (115%), indicating poor moisture resistance, while F6 demonstrated a moderate value of 85%.

Compared to the commercial product (37%), all developed formulations exhibited higher water absorption, reflecting the inherent hydrophilic nature of collagen-based materials. Water absorption in such systems is governed by fiber polarity, capillary diffusion, and microvoid formation within the composite structure.

Chemically, collagen is inherently hydrophilic due to the presence of peptide bonds, hydroxyl groups from hydroxyproline residues, and residual carboxyl groups. These polar functional groups facilitate water molecule adsorption through hydrogen bonding and dipole–dipole interactions. The alkaline treatment applied in this study may partially deprotonate acidic groups, increasing surface roughness and improving interfacial contact; however, excessive treatment may also promote microvoid formation, thereby increasing water affinity.

The binder system also plays a significant role in controlling moisture uptake. In PVAc-dominated formulations, acetate groups contribute to moderate hydrophilicity, whereas latex-rich systems, composed primarily of polyisoprene chains, exhibit more hydrophobic characteristics. The relatively low water absorption observed in F4 suggests improved pore sealing and reduced capillary pathways, likely due to better

matrix continuity and higher crosslink density.

Although the water absorption of F6 (85%) remains relatively high, such behavior is typical for collagen-based composites. In practical applications, this limitation may be mitigated through additional surface treatments or coatings to enhance moisture resistance.

Previous studies have shown that water uptake can adversely affect composite performance. Dhakal et al. (2007) reported that moisture absorption reduces mechanical properties due to matrix plasticization and interfacial weakening. Furthermore, the alkaline treatment process may enhance mechanical interlocking, as reported by Mwaikambo and Ansell (2002), although excessive porosity during curing can create pathways for water diffusion. Kabir et al. (2012) and Sgriccia et al. (2008) emphasized that surface chemistry modification is essential to reduce hydrophilicity and improve long-term durability.

Structure–Property Relationship and Engineering Trade-Off

The results reveal a clear trade-off between mechanical performance and moisture resistance among the developed formulations. Formulation F3 demonstrated the highest tensile and tear strength, indicating superior load-bearing capacity and effective stress transfer within

the composite structure. However, its relatively high water absorption (69%) suggests increased hydrophilicity associated with the presence of polar functional groups.

In contrast, formulation F4 exhibited lower water absorption (64%), indicating improved resistance to moisture penetration, while still maintaining relatively high mechanical strength. This behavior suggests the formation of a more compact and less permeable structure, likely due to improved pore coverage and network continuity.

Formulation F6 presented a more balanced performance profile, combining moderate tensile strength (0.531 N/mm²), tear resistance (1.182 N/mm), acceptable hardness (58.9 Shore A), and controlled water absorption (85%). Although its mechanical strength is lower than that of F3, its overall performance is closer to the commercial product, making it more suitable for practical insole applications where both durability and moisture stability are required.

These findings indicate that binder composition governs the balance between interfacial bonding and moisture sensitivity, highlighting the importance of optimizing formulation design based on specific application requirements.

To quantitatively evaluate this balance, an Engineering Performance Index (EPI) was introduced, defined as:

$$EPI = \frac{\text{Tensile Strength} + \text{Tear Strength}}{\text{Water Absorption}}$$

where tensile strength is expressed in N/mm², tear strength in N/mm, and water absorption in %. The resulting EPI is presented as a dimensionless comparative index.

As an example, the EPI value for formulation F3 can be calculated as:

$$EPI_{F3} = \frac{3.048 \times 5.192}{69} - 0.229$$

where tensile strength is expressed in N/mm², tear strength in N/mm, and water absorption in %. The resulting EPI is presented as a dimensionless comparative index.

As an example, the EPI value for formulation F3 can be calculated as:

Based on this calculation, formulation F3 exhibits a relatively high EPI value due to its superior mechanical strength, despite its relatively higher water absorption. This index integrates load-bearing capacity and crack resistance (numerator) with moisture sensitivity (denominator), where water absorption is treated as a performance penalty factor due to its negative impact on dimensional stability and long-term durability.

It should be noted that the EPI is intended as a simplified comparative metric rather than an absolute performance indicator.

Based on mechanical testing results, formulation F3 exhibited the highest tensile strength (3.048 N/mm²) and tear strength (5.192 N/mm), confirming strong interfacial bonding and efficient stress transfer between collagen fibers and the PVAc-containing binder. In contrast, formulation F4 demonstrated improved moisture resistance, while formulation F6 showed more stable overall performance when both mechanical and moisture-related properties were considered simultaneously. To further validate the practical applicability of the developed composite, the performance of formulation F6 was benchmarked against international standards for footwear insole materials, including ISO 20871 and ASTM D1052. These standards generally require insole materials to possess adequate tensile strength, tear resistance, flexibility, and resistance to moisture-induced degradation under repeated loading conditions. The F6 formulation exhibited tensile strength (0.531 N/mm²), tear strength (1.182 N/mm), and Shore A hardness (58.9), which fall within the acceptable range for semi-rigid and cushioning insole applications reported in polymer-based and EVA-based systems. Although the water absorption value (85%) is higher than that

of fully synthetic materials, this behavior is consistent with other bio-based composites, where hydrophilic functional groups contribute to moisture uptake.

Compared to previous studies on leather waste-reinforced composites (Sharma et al., 2023; Khan et al., 2025), the F6 formulation demonstrates a more balanced mechanical-moisture performance. This indicates that the developed LSW-based composite is not only structurally viable but also competitive with existing materials at an international level, particularly for sustainable and biodegradable footwear applications. This finding reinforces the potential of collagen-based waste materials as a viable alternative to conventional petroleum-based insole materials.

Overall, the results reveal a fundamental engineering trade-off: maximizing mechanical strength tends to increase hydrophilic sensitivity due to enhanced polar interactions and possible pore formation, whereas improving moisture resistance may reduce interfacial stress transfer efficiency.

At the molecular level, this trade-off reflects a balance between polar interaction density and network compactness. Increased polar functional group interaction enhances interfacial adhesion and mechanical strength; however, higher polarity simultaneously increases water affinity through hydrogen bonding with

absorbed moisture. Conversely, systems with lower polarity or higher crosslink density may restrict water diffusion but reduce flexible interfacial stress transfer. This molecular competition governs the overall composite performance.

These findings confirm that binder composition controls interfacial adhesion, porosity development, and crosslink density, which collectively determine the structure-property relationship of LSW-based composites. Therefore, binder engineering represents a key design strategy for tailoring collagen-based leather board toward sustainable footwear applications

Sustainable Valorization Perspective

The conversion of leather shaving waste (LSW) into composite boards aligns with sustainable material development strategies and supports circular economy principles. In addition to environmental benefits, the economic aspect of material selection is also an important consideration. From a cost-effectiveness perspective, the use of LSW as the primary reinforcement offers a significant economic advantage compared to fully synthetic insole materials. As an abundant industrial by-product, LSW has relatively low or negligible raw material cost, which can substantially reduce overall material expenditure.

Although the incorporation of binders such as polyester resin, latex adhesive, and

polyvinyl acetate (PVAc) introduces additional costs, their proportion within the composite formulation is controlled and primarily intended to enhance mechanical integrity and durability. Compared to fully synthetic polymer-based insoles, which rely entirely on virgin materials, partial substitution with LSW may result in a more economically viable material system, particularly for low- to medium-cost footwear applications. However, a detailed cost analysis, including processing efficiency and scalability, is beyond the scope of the present study and is recommended for future investigation, especially in developing regions where cost-sensitive material selection is critical. Previous studies have demonstrated the potential of leather waste fibers as reinforcing agents in eco-friendly composites (Sharma et al., 2023; Khan et al., 2025). Furthermore, Ajayi et al. (2025) highlighted the importance of developing sustainable natural fiber composites to support circular economy applications. The present study contributes to this field by demonstrating that binder optimization plays a decisive role in balancing mechanical performance and moisture resistance in LSW-based composites. Compared to conventional synthetic insole materials, the developed LSW-based composite shows that waste-derived collagen fibers can achieve functional

mechanical performance while contributing to solid waste reduction. This highlights the potential of LSW as a sustainable alternative material for footwear applications.

This study primarily focuses on evaluating the mechanical and physical performance of LSW-based composites. However, detailed microstructural and chemical characterization, such as scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR), were not conducted. Therefore, the proposed interaction mechanisms between binder systems and collagen fibers are based on theoretical considerations and supported by literature reports. Without direct spectroscopic or microscopic evidence, these interpretations should be regarded as indicative rather than conclusive. Future studies incorporating SEM and FTIR analyses are recommended to validate interfacial morphology and chemical interactions within the composite system. These findings confirm that binder composition governs the structure–property relationship of LSW-based composites. Therefore, the findings should be interpreted as indicative trends, and further studies with full statistical validation are required.

CONCLUSION

This study demonstrates the potential utilization of leather shaving waste (LSW) as a raw material for collagen-based composites through binder system engineering. The results indicate that variations in binder composition influence mechanical properties and water absorption behavior of the developed materials.

Formulation F3 exhibited the highest tensile and tear strength, while F4 showed lower water absorption, indicating improved resistance to moisture. Meanwhile, F6 presented a more balanced mechanical–moisture performance with properties comparable to the commercial product, suggesting its suitability for practical insole applications under moderate conditions.

The introduction of an Engineering Performance Index (EPI) provides a simplified approach to evaluate the trade-off between mechanical strength and moisture sensitivity, enabling comparative assessment among formulations.

It should be noted that the interpretation of binder–fiber interactions is based on macroscopic performance data. Detailed microstructural and chemical characterization, such as SEM and FTIR, were not conducted in this study. Therefore, further investigation is required to confirm the proposed interaction mechanisms.

Overall, this work highlights the role of binder system design in controlling the structure–property relationship of collagen-based composites and offers a potential pathway for the sustainable valorization of tannery solid waste. Therefore, the findings should be interpreted as indicative trends, and further studies with full statistical validation are required.

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